Atomic and Molecular Physics Program

7 March 2012

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AFOSR/RSE
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

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NAME: Tatjana Curcic

BRIEF DESCRIPTION OF PORTFOLIO:

Understanding interactions between atoms, molecules, ions, and radiation.

LIST SUB-AREAS IN PORTFOLIO:

- **Cold Quantum Gases**
  - Strongly-interacting quantum gases
  - Ultracold molecules
  - New phases of matter
  - Non-equilibrium quantum dynamics
- **Quantum Information Science (QIS)**
  - Quantum simulation
  - Quantum communication
  - Quantum metrology, sensing, and imaging
  - Cavity optomechanics

Scientific and Transformational Opportunities

Scientific Opportunities	Transformational Opportunities
Dipolar Matter, Ultracold Molecules	• Novel phases of matter • Ultracold chemistry
Quantum Memories and Interfaces	• Long-distance quantum communication
Quantum Simulation	• High-T_c superconductivity • Novel phases of matter
Quantum Metrology and Sensing	• Ultra-high-precision clocks • High-resolution, high-sensitivity magnetometry • High-sensitivity gravimetry • Precision inertial navigation in GPS-denied environments
Non-equilibrium Quantum Dynamics	• Dynamic control of materials • Efficient optical devices

Outline

- Quantum Simulation, Strongly-Interacting Quantum Gases
  - **Bosons: Markus Greiner, Harvard (MURI)**
    - **Algorithmic Cooling in Quantum Gases**
      Waseem Bakr, *et al, Nature* **480**, 500 (2011)
    - **Quantum Magnetism**
      Jonathan Simon, *et al, Nature* **472**, 307 (2011)

  - **Fermions: Martin Zwierlein, MIT (PECASE, MURI)**
    - **Evolution of Fermi Pairing from 3D to 2D**
      Ariel T. Sommer*, et al, Phys. Rev. Lett*. **108**, 045302 (2012)
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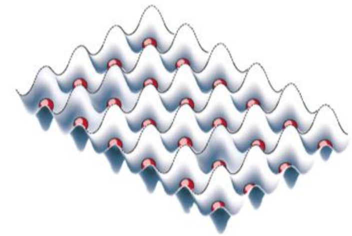
    Mingwu Lu*, et al, Phys. Rev. Lett.* **107**, 190401 (2011)

- Quantum Metrology: Till Rosenband, NIST
  - **Coherent Drive Spectroscopy**
    D.B. Hume*, et al, Phys. Rev. Lett.* **107**, 243902 (2011)

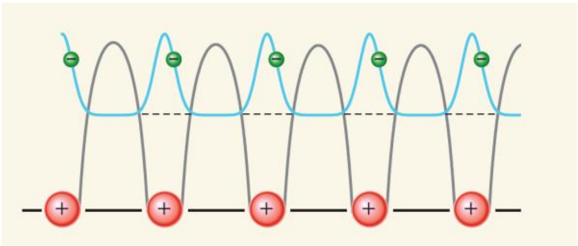
Strongly-correlated quantum gases

Optical lattices



Atoms interact strongly on lattice sites
Superfluid - Mott insulator transition

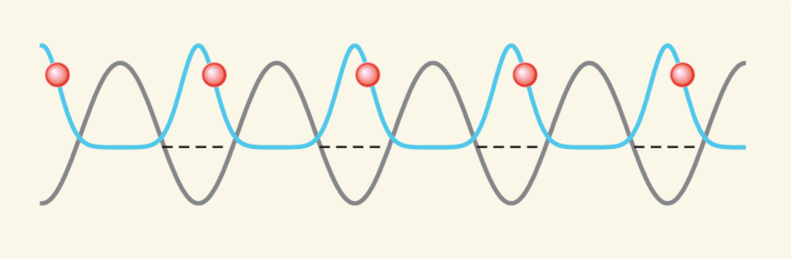
Synthetic matter, quantum simulations



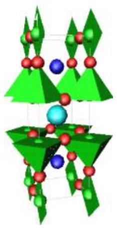
Electrons in a crystal lattice

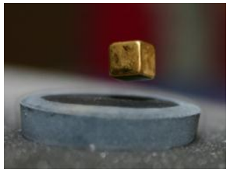
↕

Atoms in an optical lattice

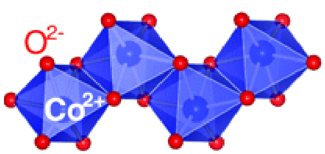


Strongly correlated materials

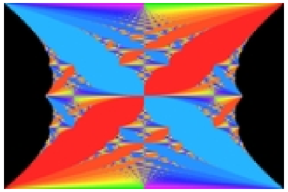




High Tc superconductors



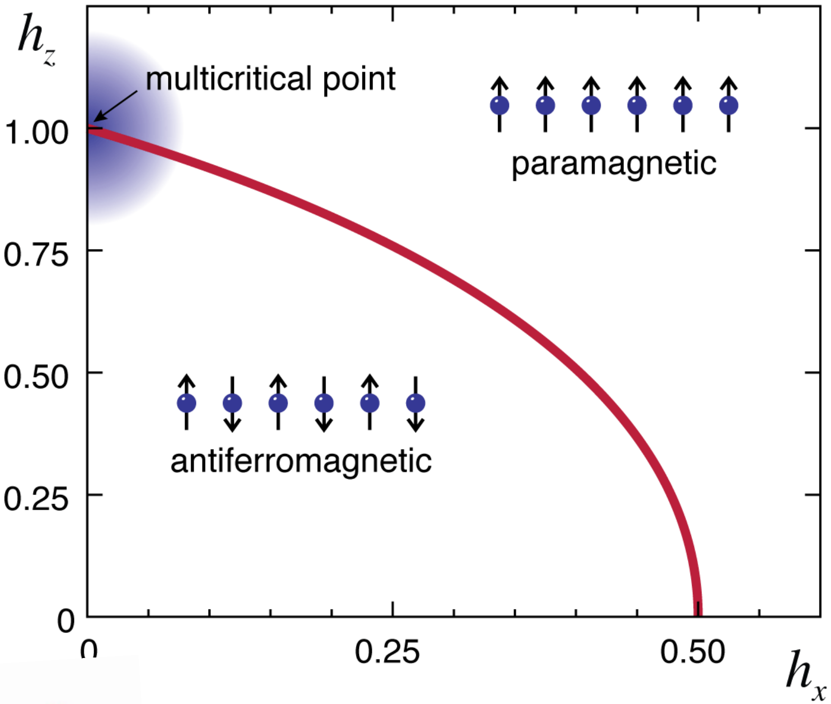
Quantum magnets

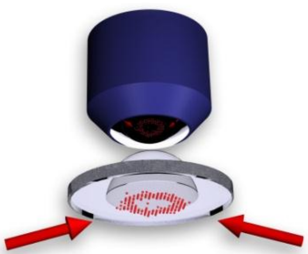


Quasi-low dimensional materials

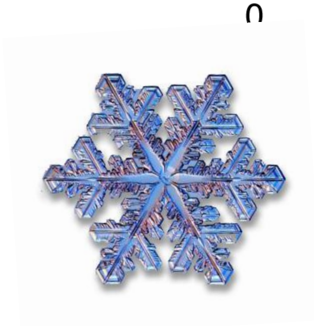
Quantum magnetism

Ising model:
quantum phase transition from paramagnet to antiferromagnet

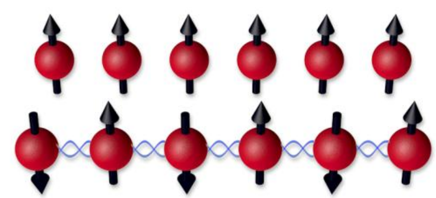




Quantum gas microscope



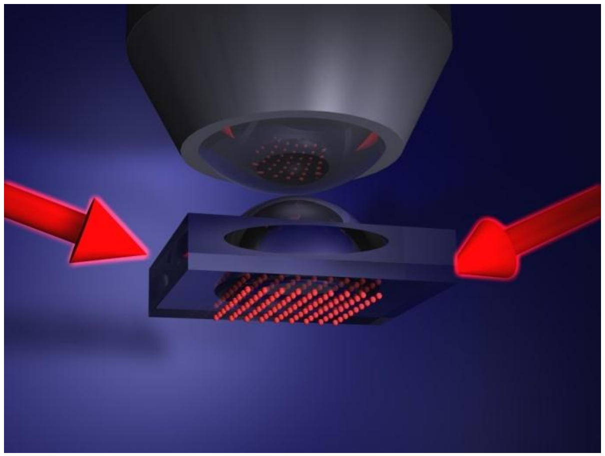
Algorithmic cooling

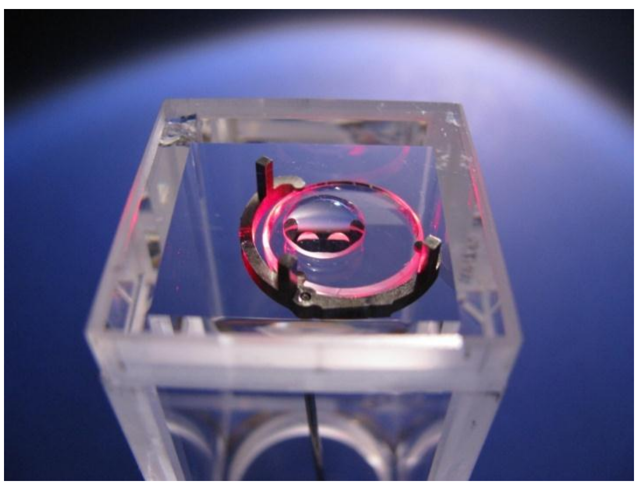


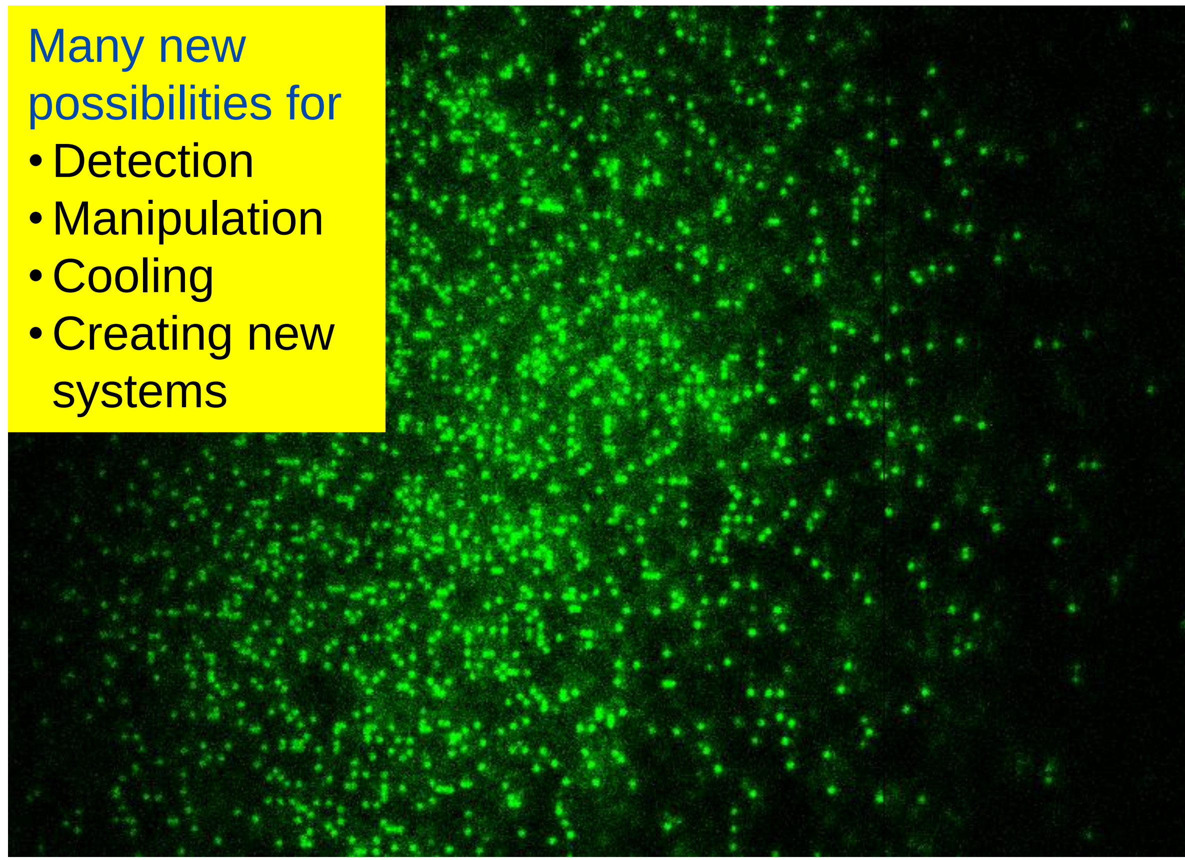
Quantum magnetism

Quantum Gas Microscope

Waseem S. Bakr, *et al*, *Nature* **463**, 74 (2009)

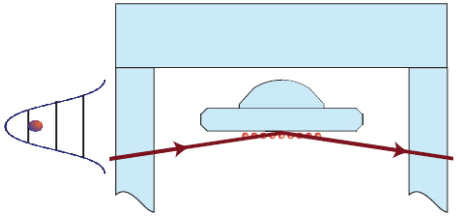






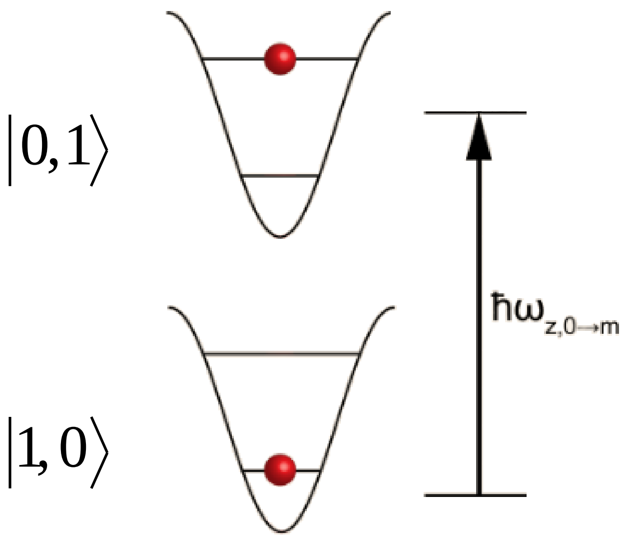
Many new possibilities for
- Detection
- Manipulation
- Cooling
- Creating new systems

Interaction induced orbital excitation blockade



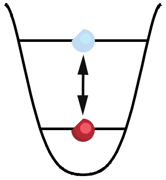
Axial vibrational excitation

$$\left| n_{ground}, n_{excited} \right\rangle$$



Orbital excitation blockade operations

$n_{tot} = n+m$



$$|n,m\rangle \rightarrow |n-1,m+1\rangle$$

$|1,0\rangle \leftrightarrow |0,1\rangle$

$|2,0\rangle \leftrightarrow |1,1\rangle$

$|3,0\rangle \leftrightarrow |2,1\rangle$

1
2
3
4

4 3 2 1 n

-650Hz -440Hz -220Hz 0Hz $\frac{\Delta\omega_z}{2\pi}$

Algorithmic cooling

Random occupation

↓

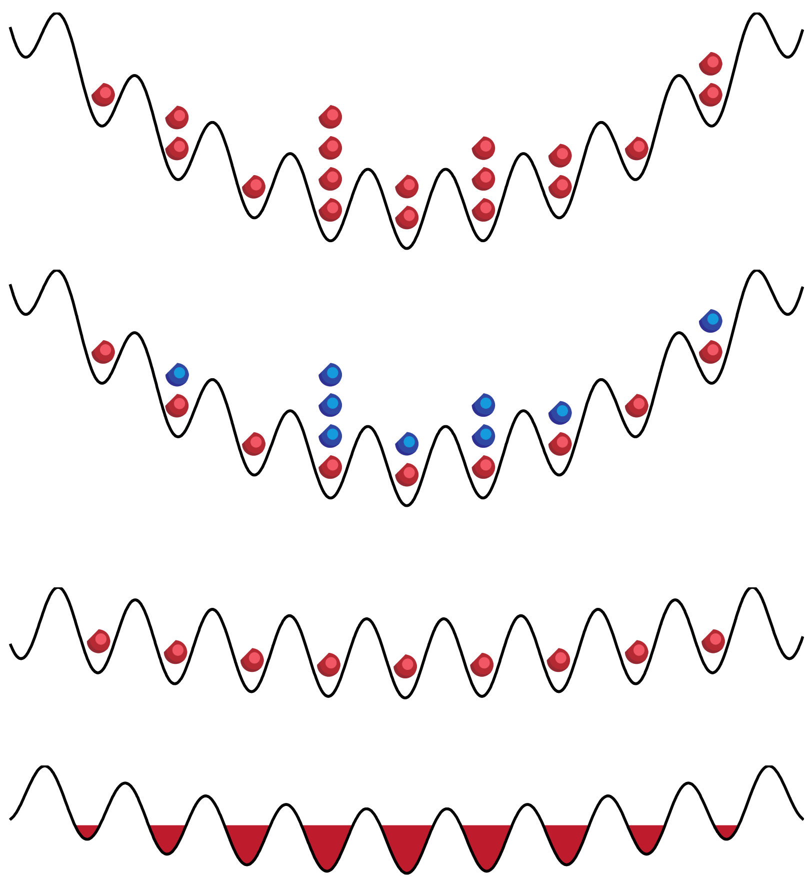
Filter operations
4→3, 3→2, 2→1

↓

Mott insulator

↓

Superfluid



Algorithmic cooling

Random occ

↓

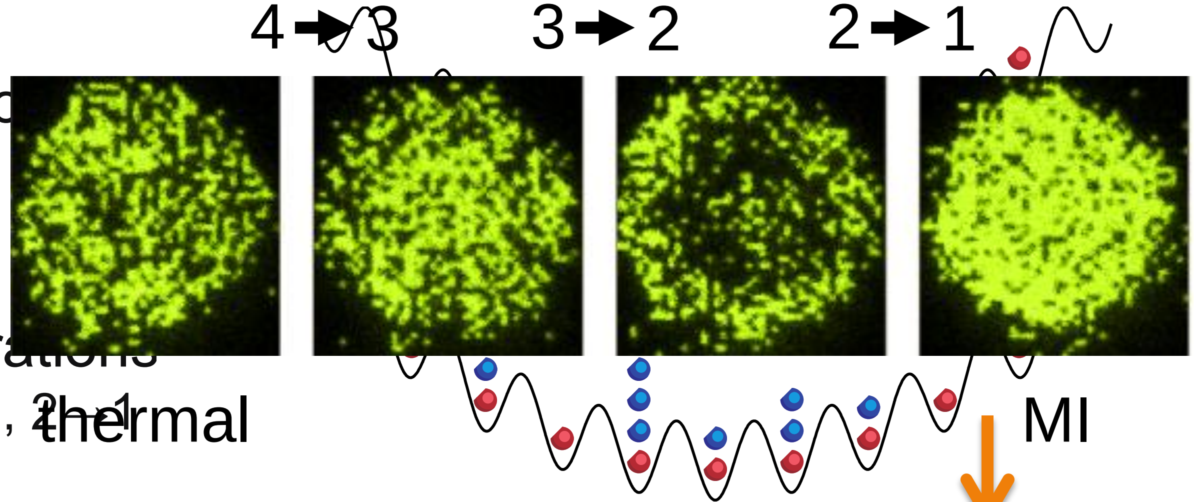
Filter operations
4→3, 3→2, 2→1

↓

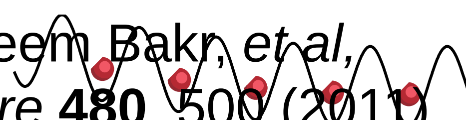
Mott insulator

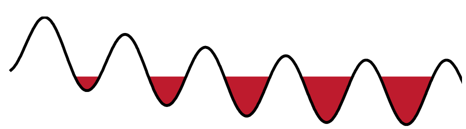
↓

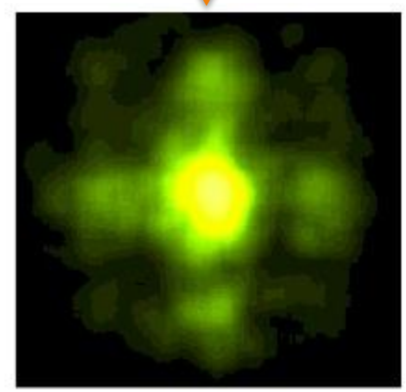
Superfluid



Waseem Bakr, *et al, Nature* **480**, 500 (2011)



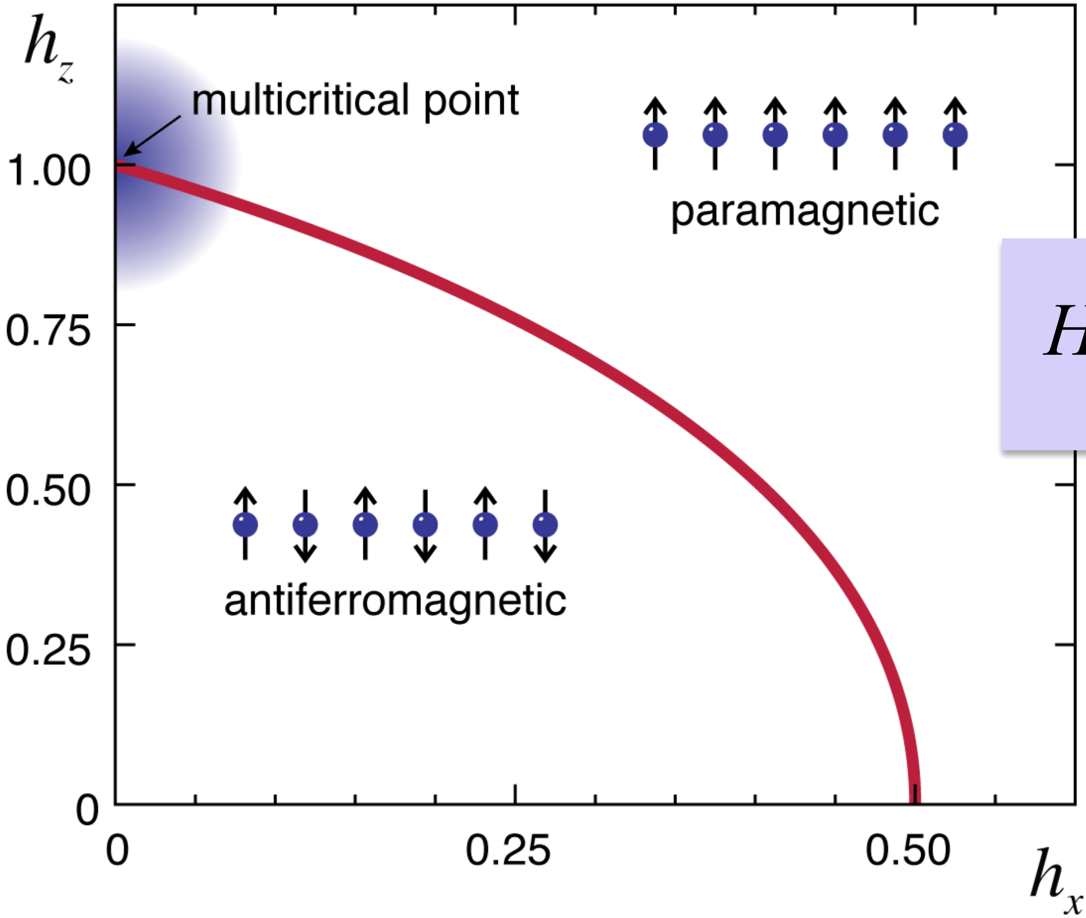




Recooled superfluid

Quantum Magnetism

Quantum simulation of an antiferromagnetic Ising spin chain

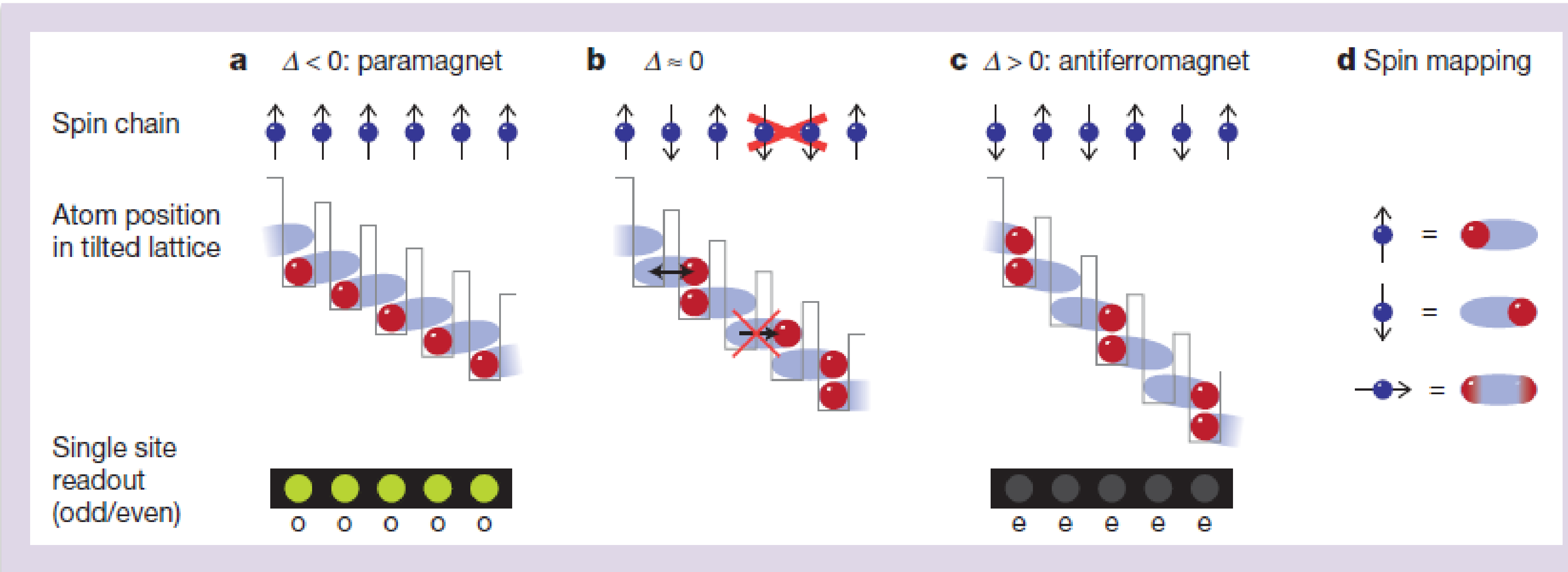


$$H = J\sum_i S_z^i S_z^{i+1} - h_z S_z^i - h_x S_x^i$$

hx =0: classical first order phase transition

Finite hx: quantum phase transition, second order

Tilted Hubbard Model and Mapping to Spin Model



realizes constraint *drives transition*

$$H = J\sum_i \Big[\overbrace{S_z^i S_z^{i+1} - (1-}^{\text{realizes constraint}}\overbrace{\tilde{\Delta})\, S_z^i - 2^{3/2}\tilde{t}\, S_x^i}^{\text{drives transition}} \Big]$$

$$\underbrace{(1-\tilde{\Delta})}_{h_z} \qquad \underbrace{2^{3/2}\tilde{t}}_{h_x}$$

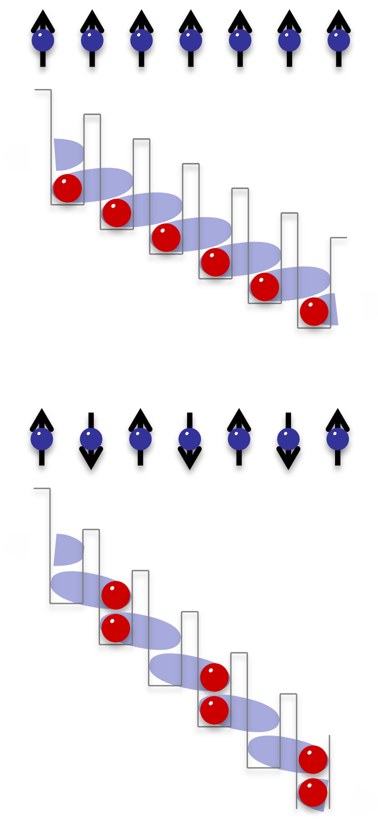
$$\Delta = E - U$$

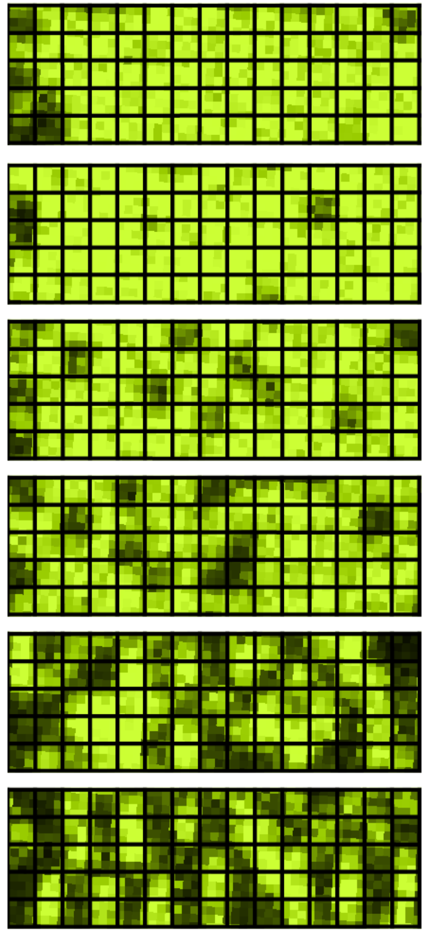
E: energy difference per lattice site, or lattice tilt

U: onsite interaction

Adiabatic transition to the AF state

Jonathan Simon, *et al, Nature* **472**, 307 (2011)

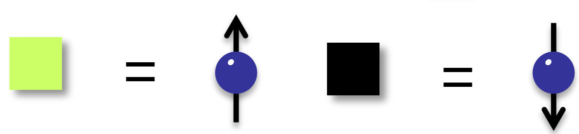




- High magnetic field: *spins align with field*

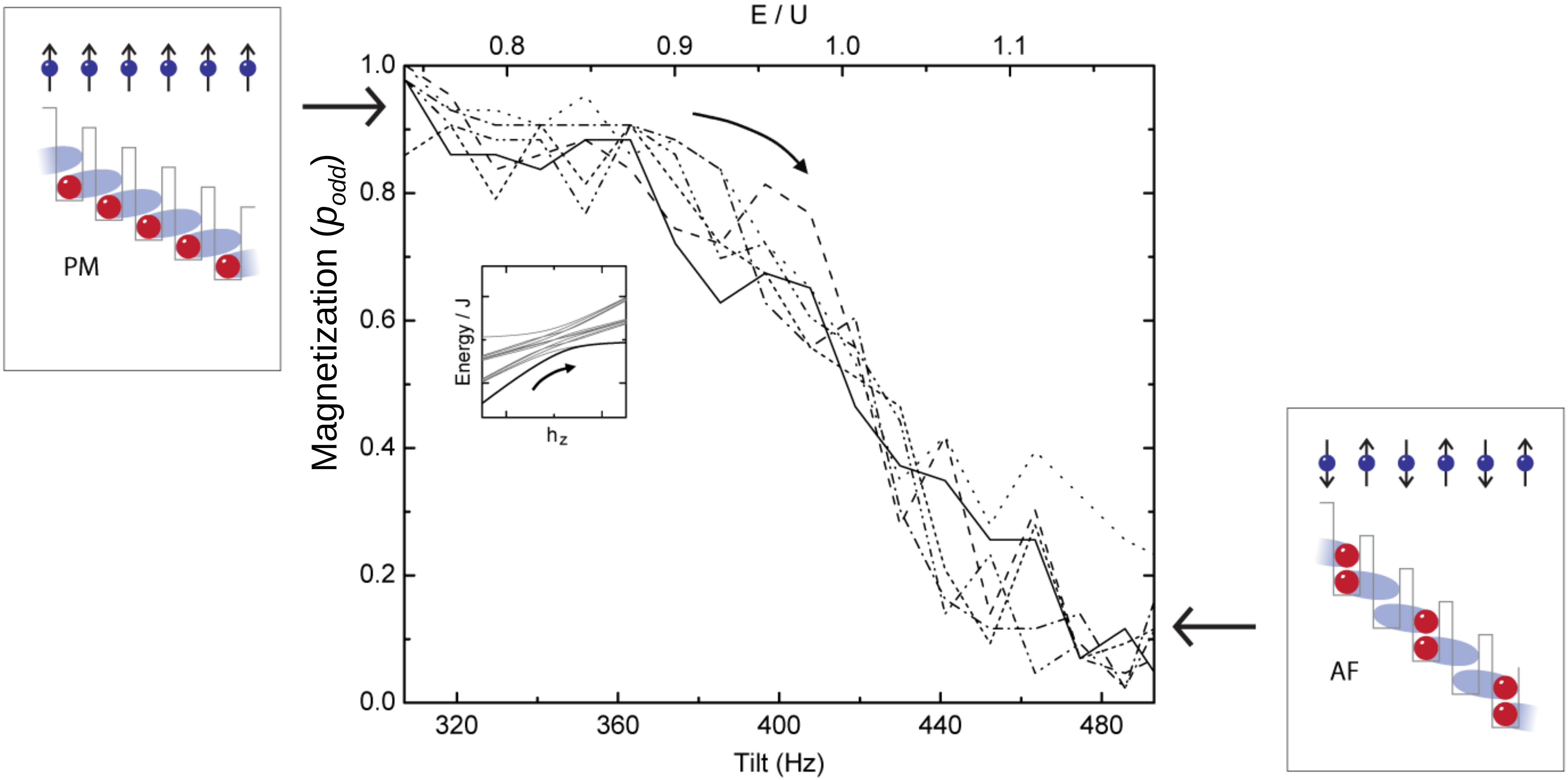
- Low magnetic field: antiferromagnetic interactions dominate, producing *Neel order*

Modulation spectroscopy: turn double occupancy into single occupancy



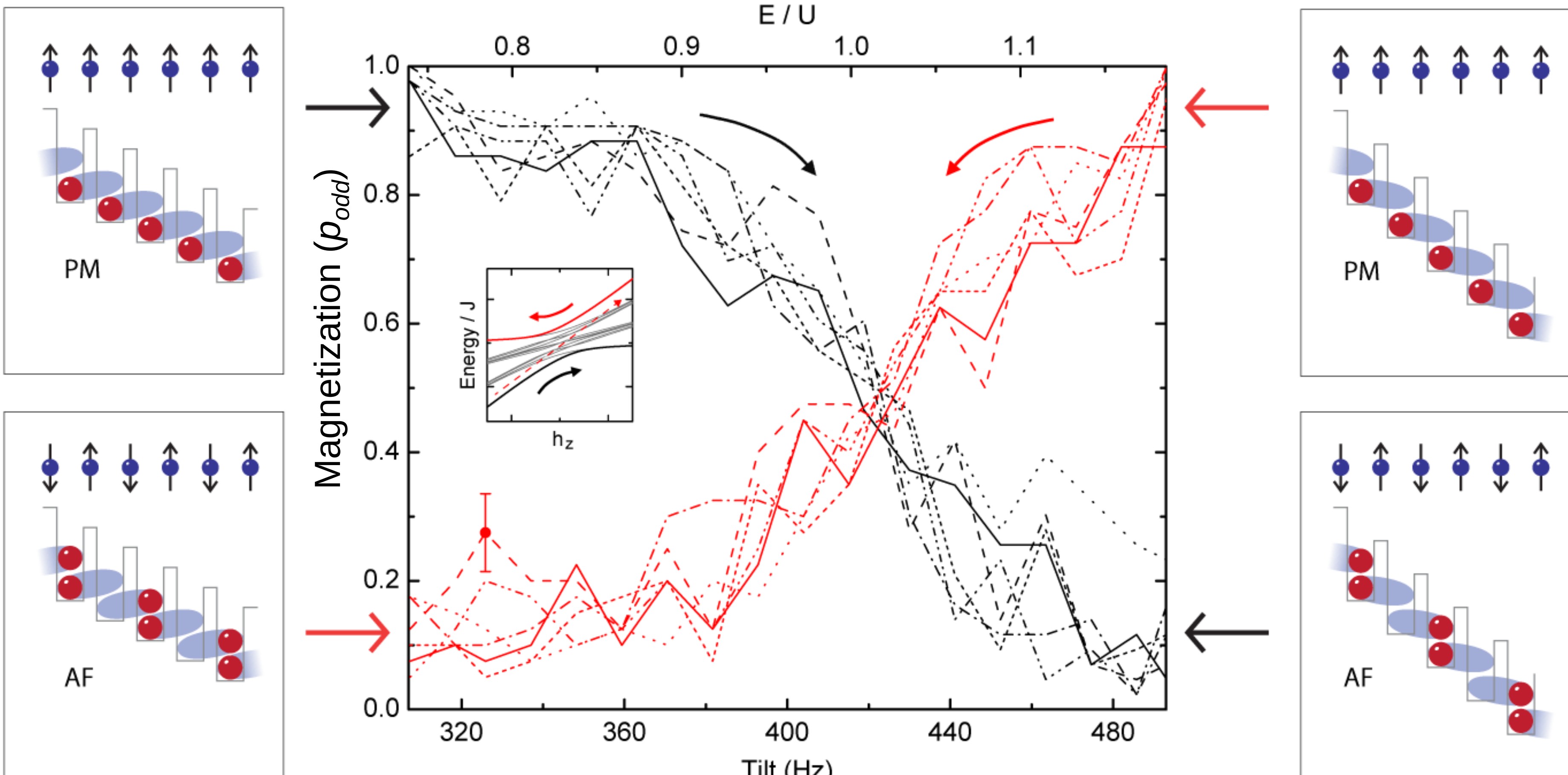
Direct spin imaging preliminary

Selecting homogeneous domain



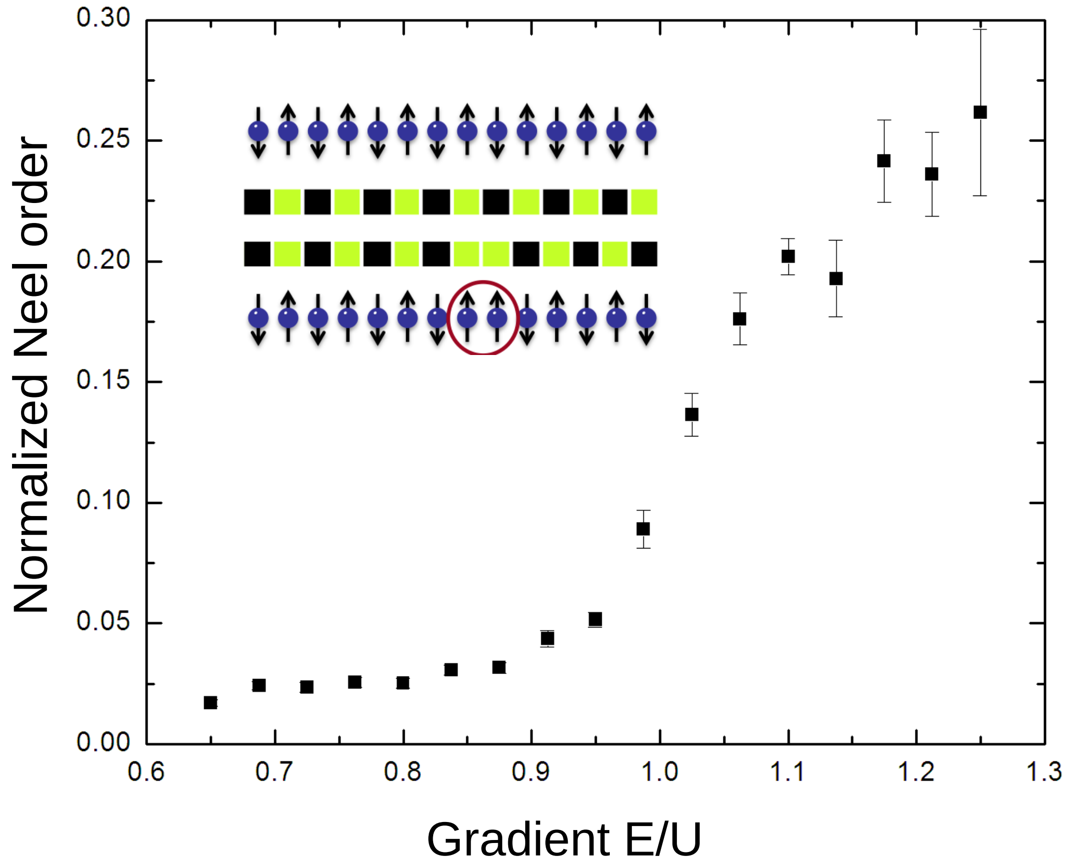
- 6 adjacent sites that transition simultaneously (RMS shift 6 Hz)
- Compare to 10%-90% width (105 Hz) and transverse field (28 Hz)

Transitioning at highest and lowest energy many-body state



Jonathan Simon, *et al*, *Nature* **472**, 307 (2011)

Direct measurement of Neel order parameter



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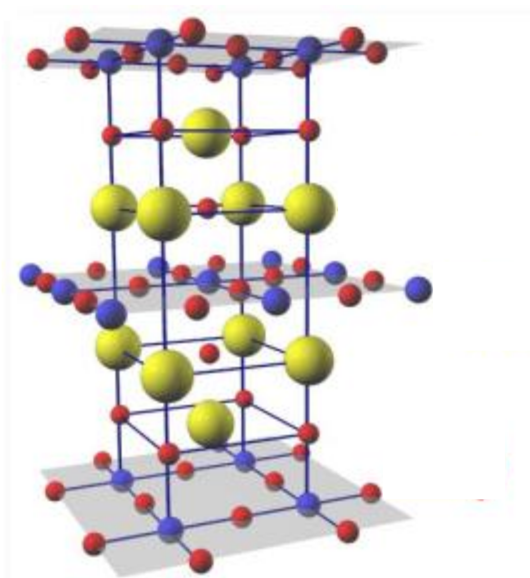
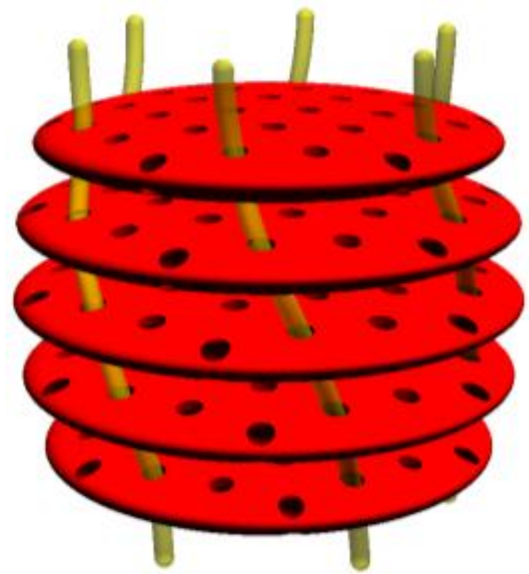
Strongly Interacting Fermi Gases in coupled quasi-2D layers



High-T_c Superconductor with stacks of CuO planes



Stacks of 2D coupled fermionic superfluids

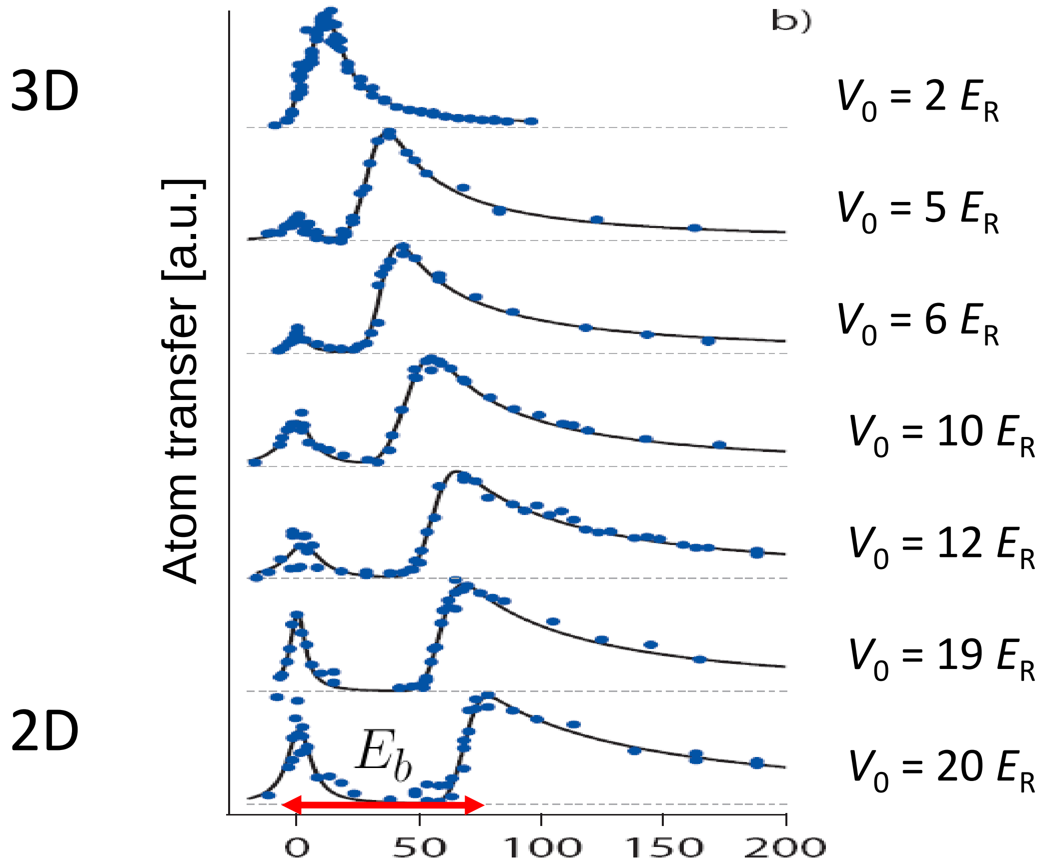
- Access physics of layered superconductors
- Evolution of Fermion Pairing from 3D to 2D
- Berezinskii-Kosterlitz-Thouless transition in deep 2D limit

Evolution of Fermion Pairing from 3D to 2D

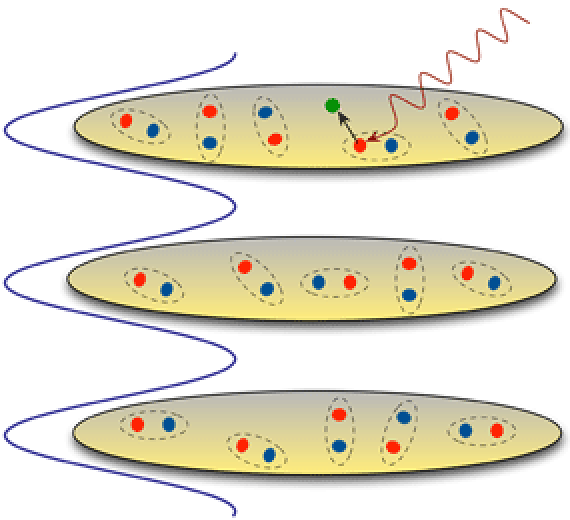
Ariel T. Sommer, *et al*, *Phys. Rev. Lett*. **108**, 045302 (2012)

Density of States: 3D ~ $\sqrt{\varepsilon}$
2D $const.$

Direct consequence:
Always a bound state in 2D

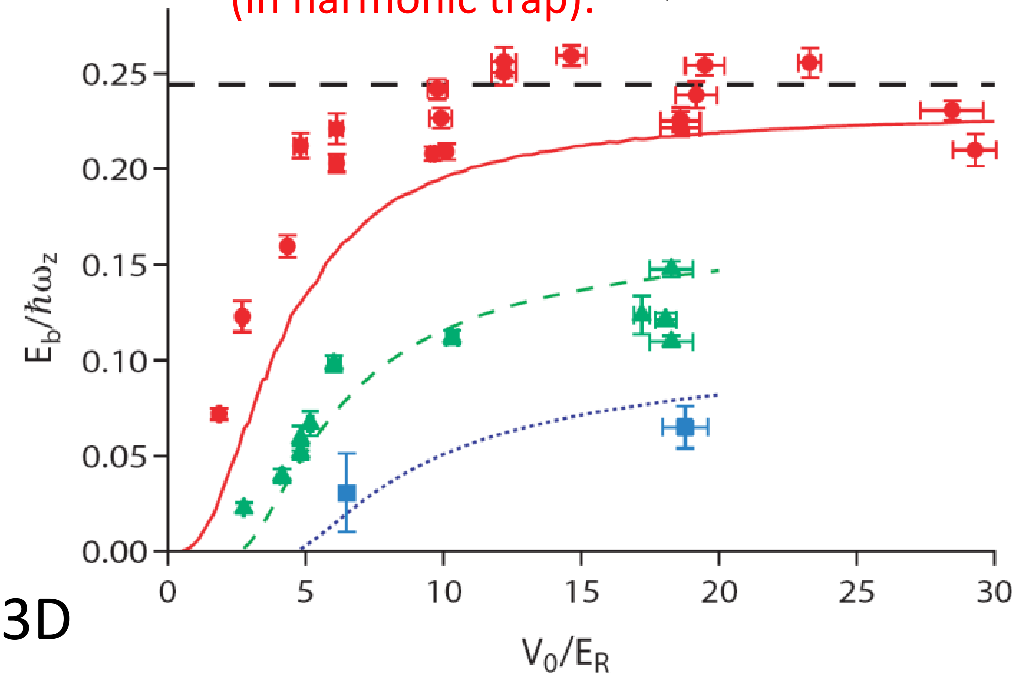


RF spectroscopy:



Evolution of Fermion Pairing from 3D to 2D

On Resonance (in harmonic trap): $E_{B,th} = 0.244\hbar\omega_z$



3D

2D

Resonance
d/a = 0

3D BCS
d/a = -1.2

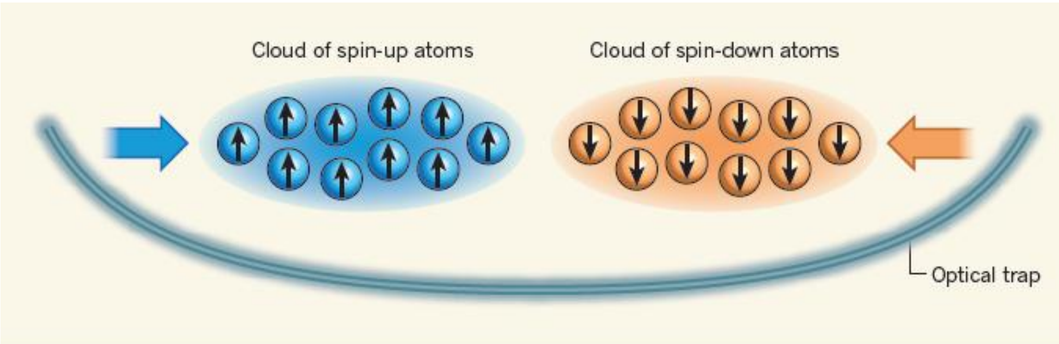
3D BCS
d/a = -2.7

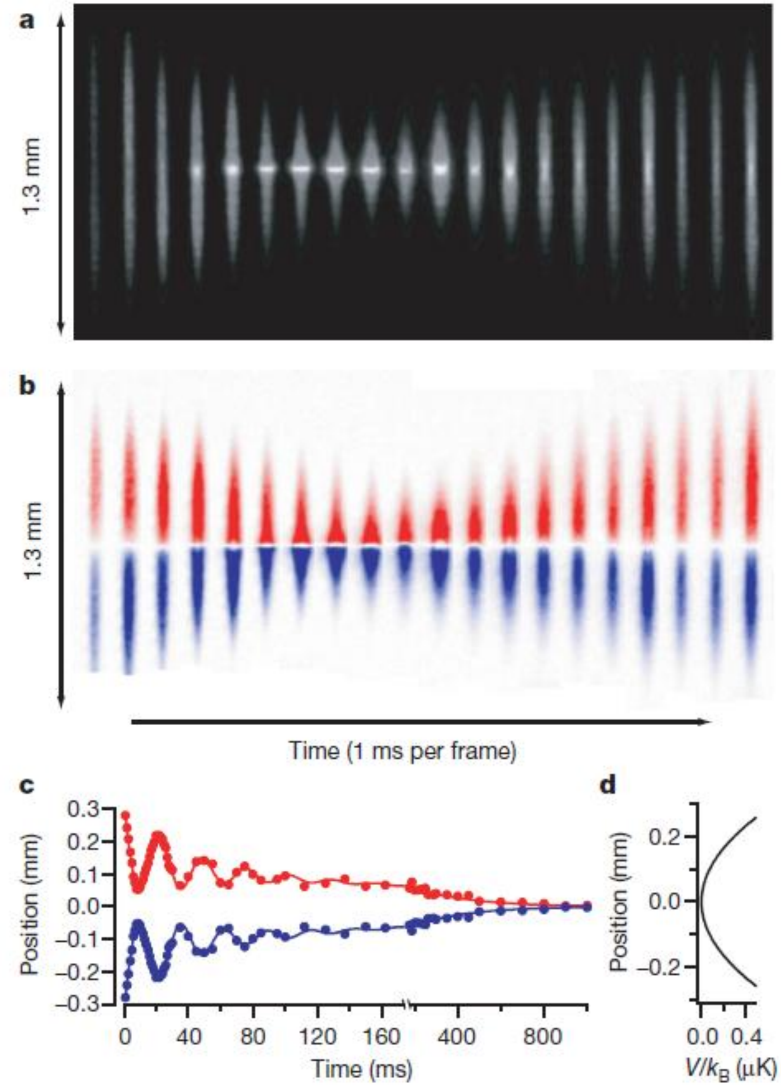
- Observed fermion pairing from 3D to 2D
  - →Are those pairs superfluid?
  - →Study coherence, thermodynamics, rotation…
  - →What is T_C as a function of interlayer tunneling?

Towards a recipe for high T_C

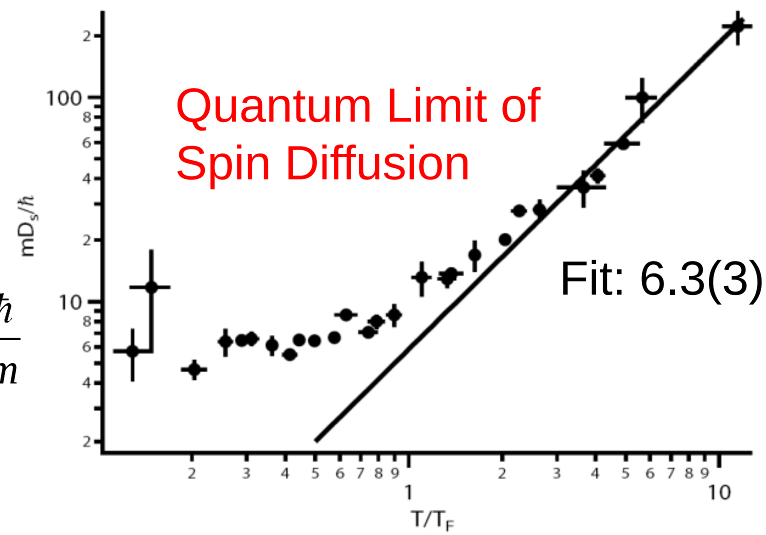
Spin Transport – “Little Fermi Collider” (LFC)

Ariel Sommer, *et al, Nature* **472**, 201 (2011)





Spin Diffusion vs. Temperature



Quantum Limit of Spin Diffusion

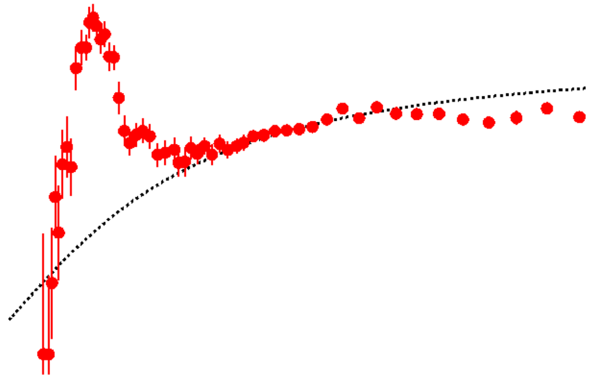
$$5.8\frac{\hbar}{m}$$

Fit: $6.3(3)\frac{\hbar}{m}\left(\frac{T}{T_F}\right)^{3/2}$

Thermodynamics of the Strongly-Interacting Fermi Gas

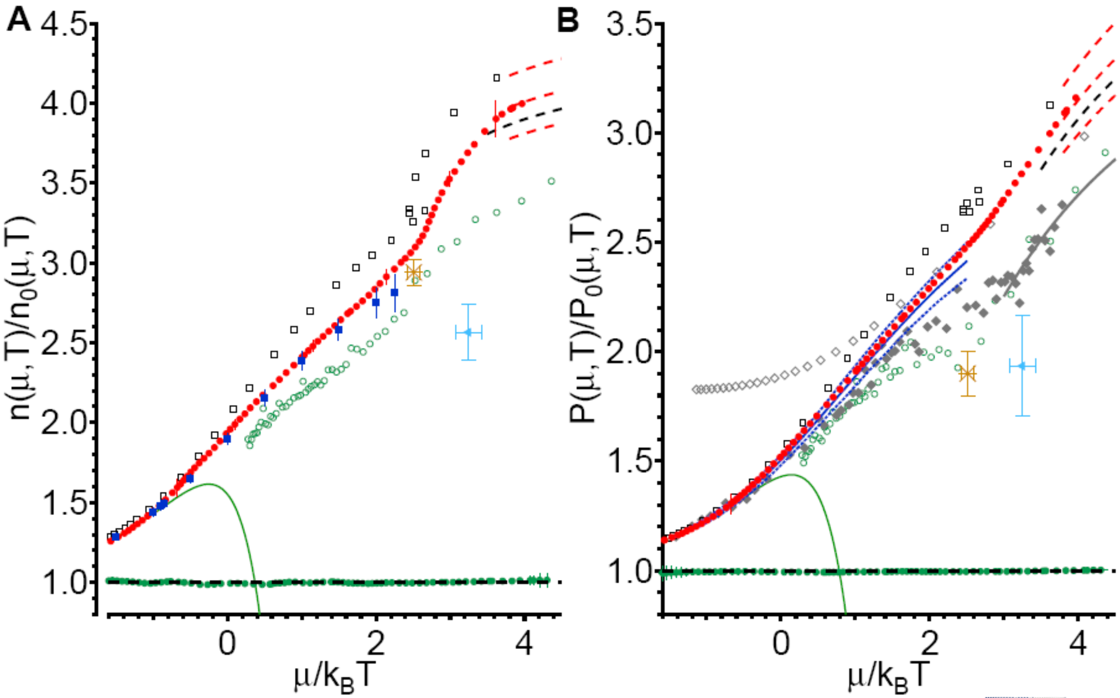
Revealing the Superfluid Lambda Transition in a Fermi Gas

Mark J.H. Ku, *et al, Science* (in print)



“Feynman diagrams versus Feynman quantum emulator”

K. Van Houcke, *et al* (submitted to *Nature Physics*)



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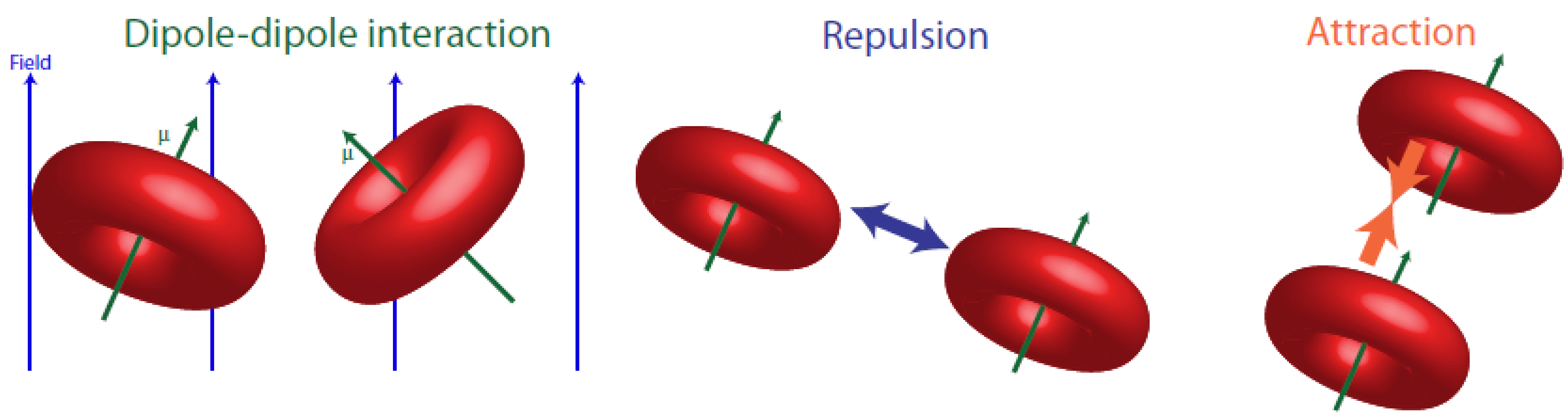
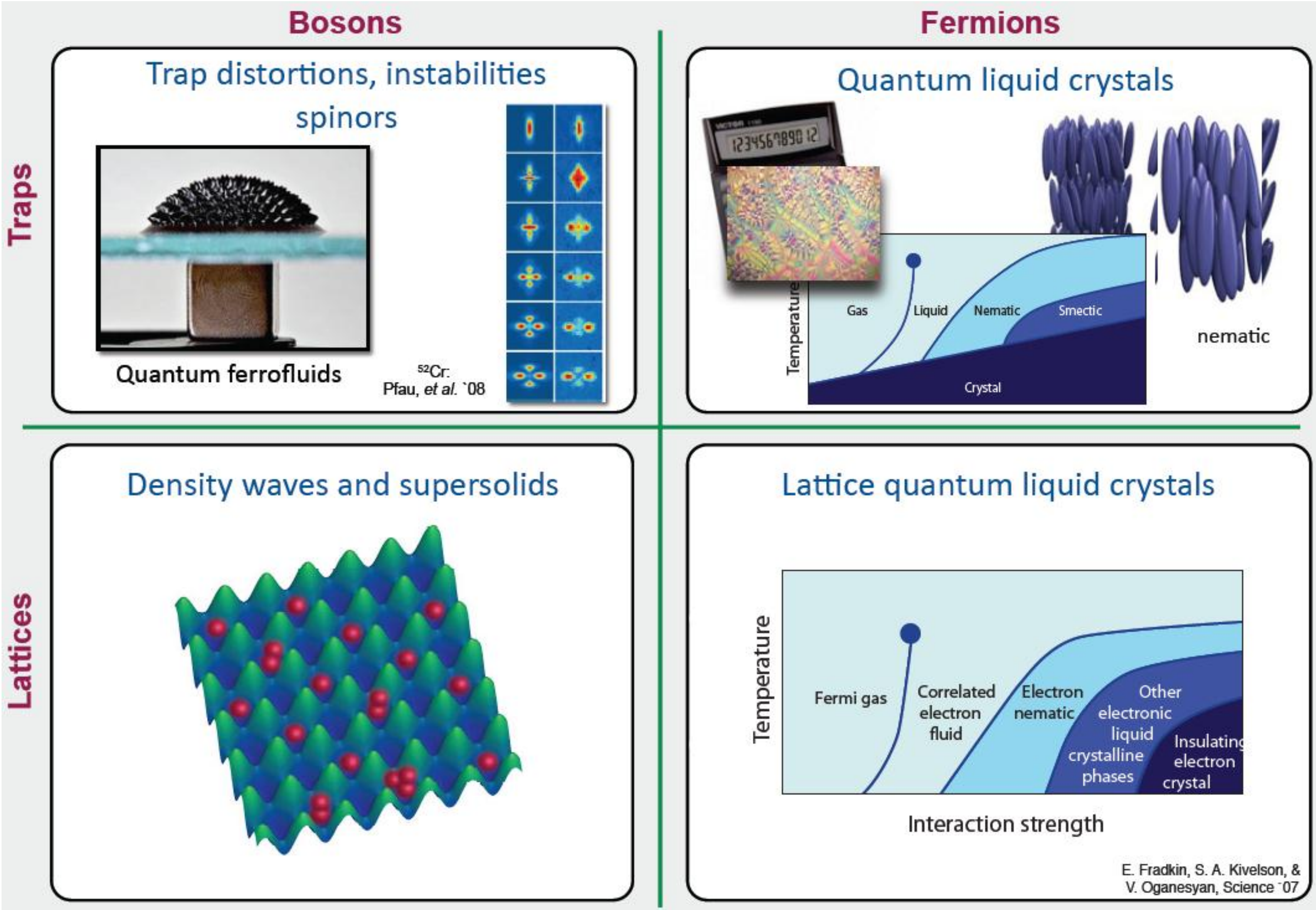
Ultracold Dipolar Physics

- Exploit strong, long-range r^{-3}, and anisotropic dipole-dipole interaction

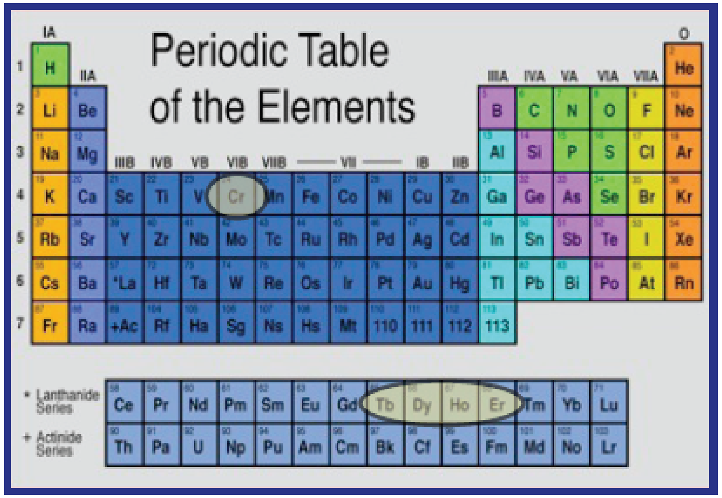
$$V_d(r) = \frac{d^2}{r^3}(1 - 3\cos^2\theta)$$



Ultracold dipolar Bose and Fermi gases: Exotic quantum phases



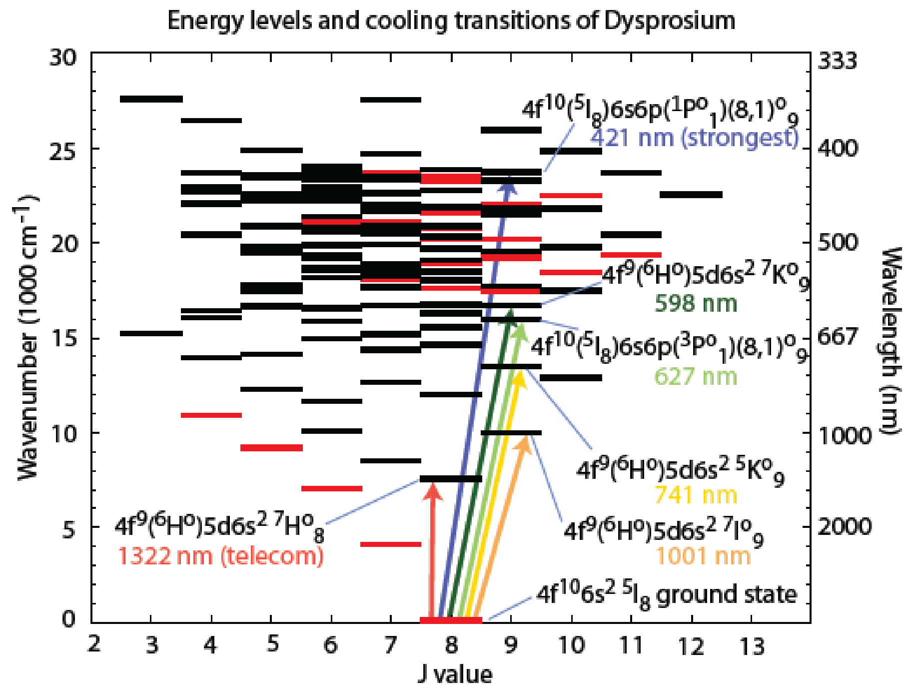
Laser cooling Dysprosium

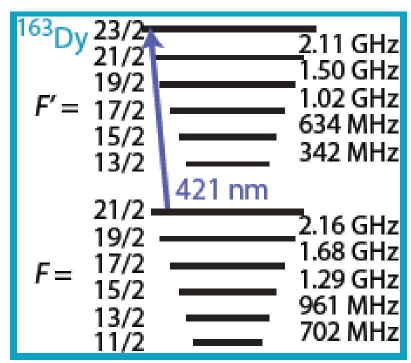


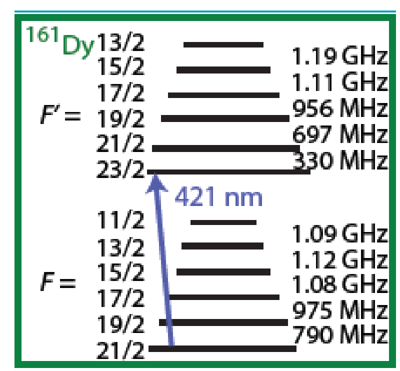
$\mu = 10\ \mu_B$!

Rb: 200x $\mu^2 m$

Cr: 9x $\mu^2 m$







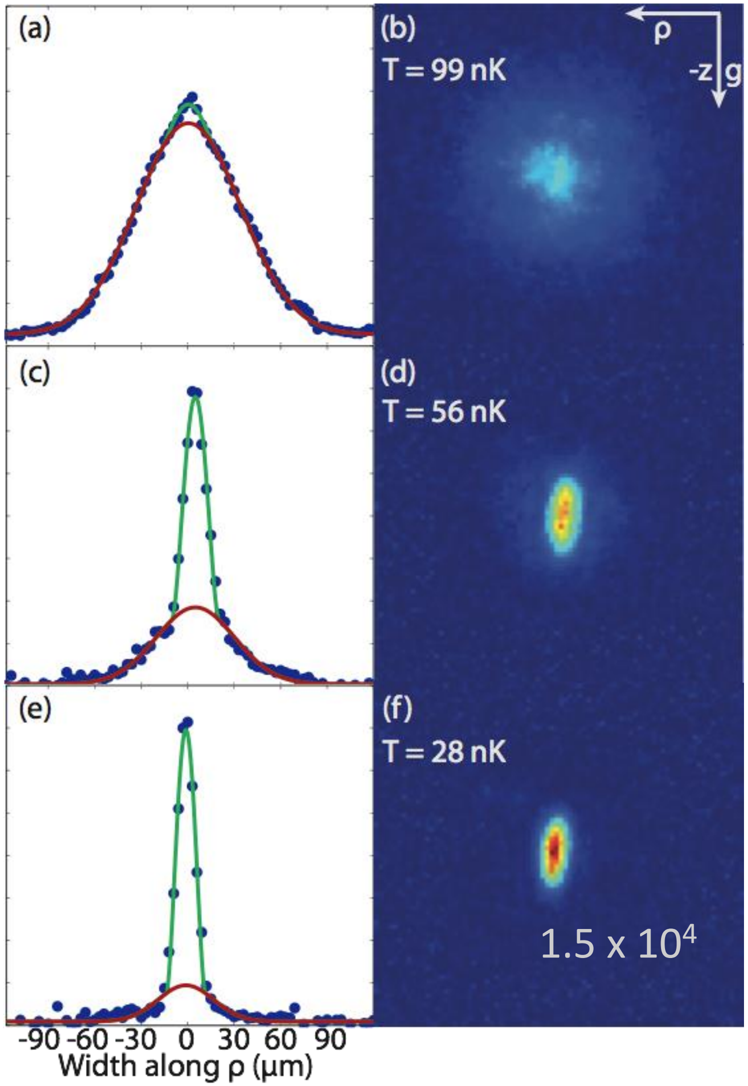
Five isotopes, 3 bosons (I=0), 2 fermions (I=5/2)

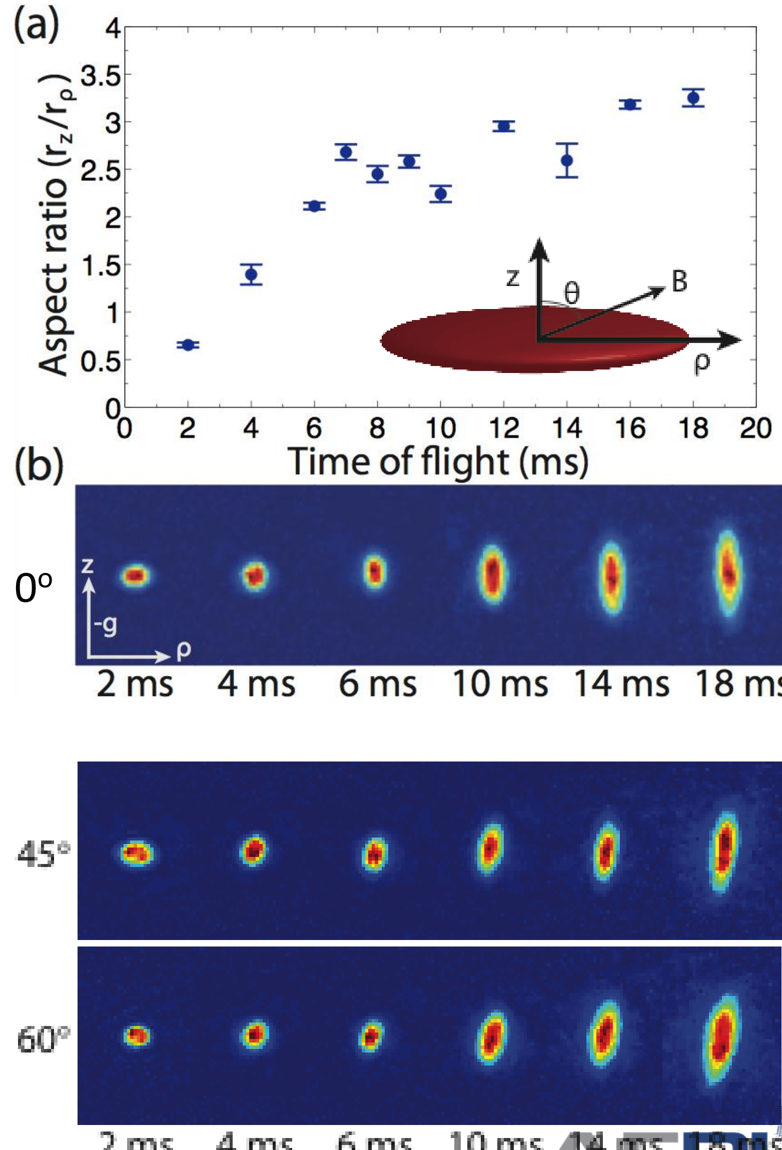
Er MOT: McClelland & Hanssen PRL '06

Strongly Dipolar Dy BEC

M. Lu, N. Burdick, S.-H. Youn, and B. Lev, *Phys. Rev. Lett.* 107 190401 (2011)

BECs of ^{164}Dy and ^{162}Dy

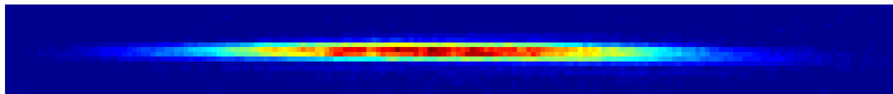


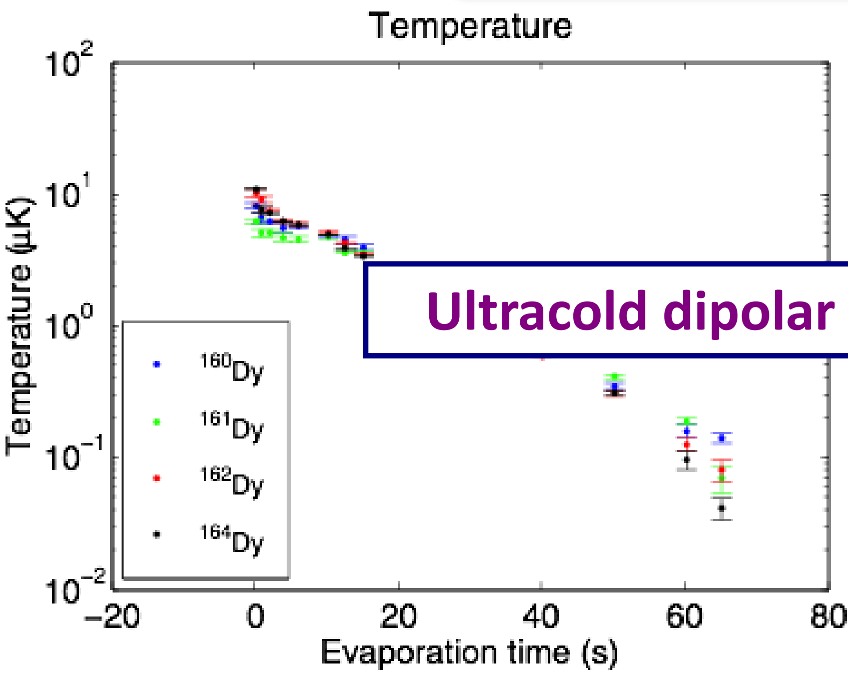


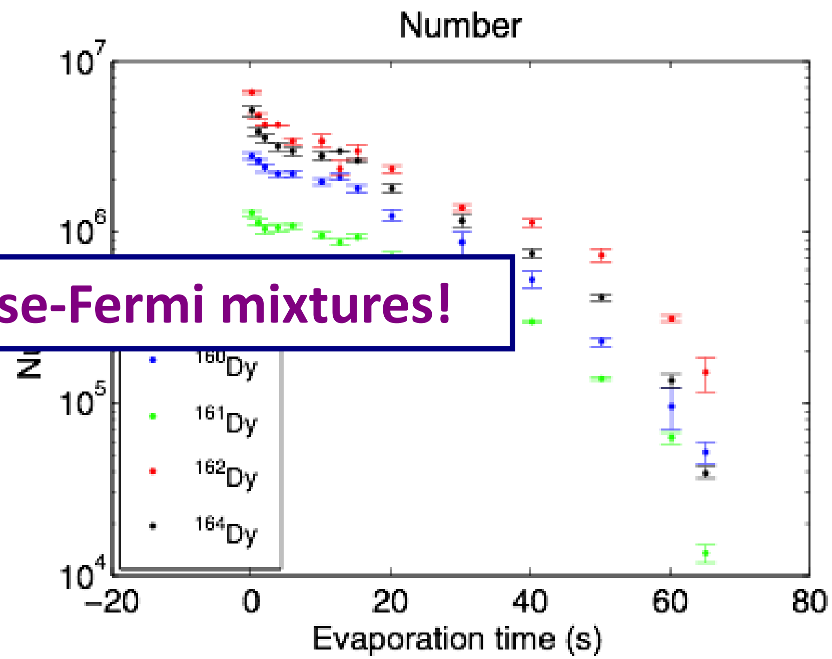
Evaporative cooling of all isotopes

Including identical fermions! T/T_F = 1.3 in crossed ODT

Single beam ODT







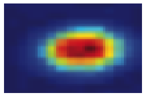
Ultracold dipolar Bose-Fermi mixtures!

Universal dipolar scattering?

Bohn, Cavagnero, Ticknor, New J. Phys. `09

First dipolar degenerate Fermi gas!

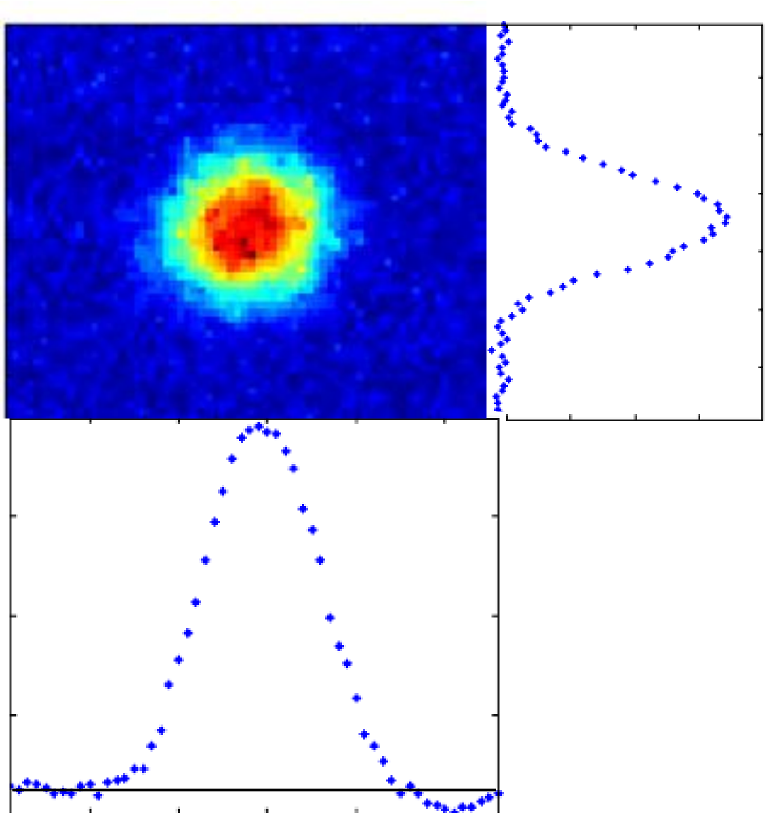
^{161}Dy Sympathetically cooled with ^{161}Dy to $T/T_F < 0.3$



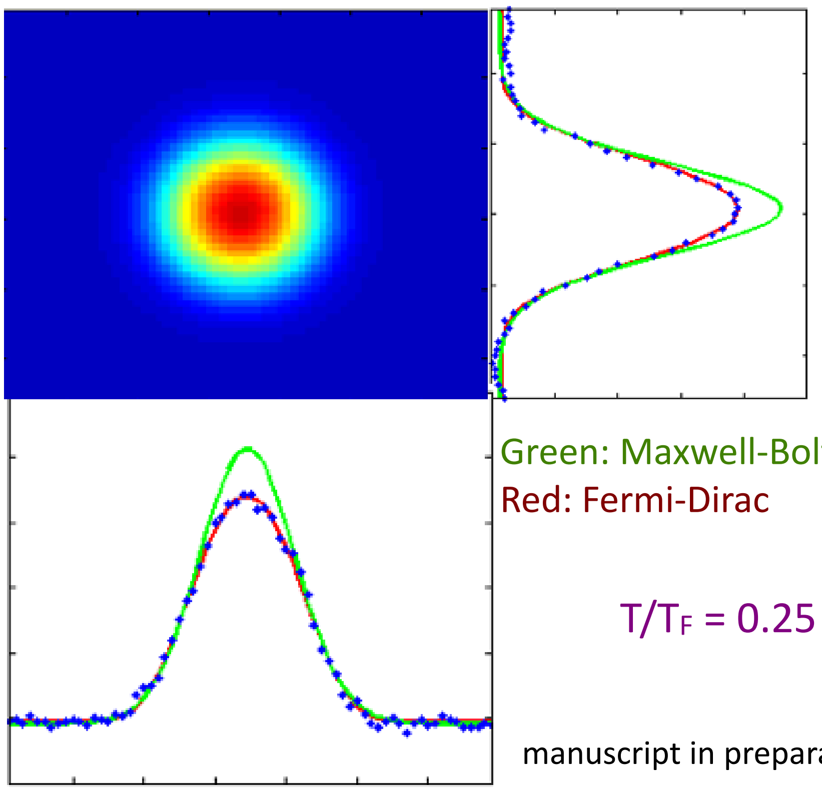
Oblate initial trap

Fermionic ^{161}Dy time-of-flight expansion

Single shot: 6×10^3 atoms



Average of three shots



Green: Maxwell-Boltzmann

Red: Fermi-Dirac

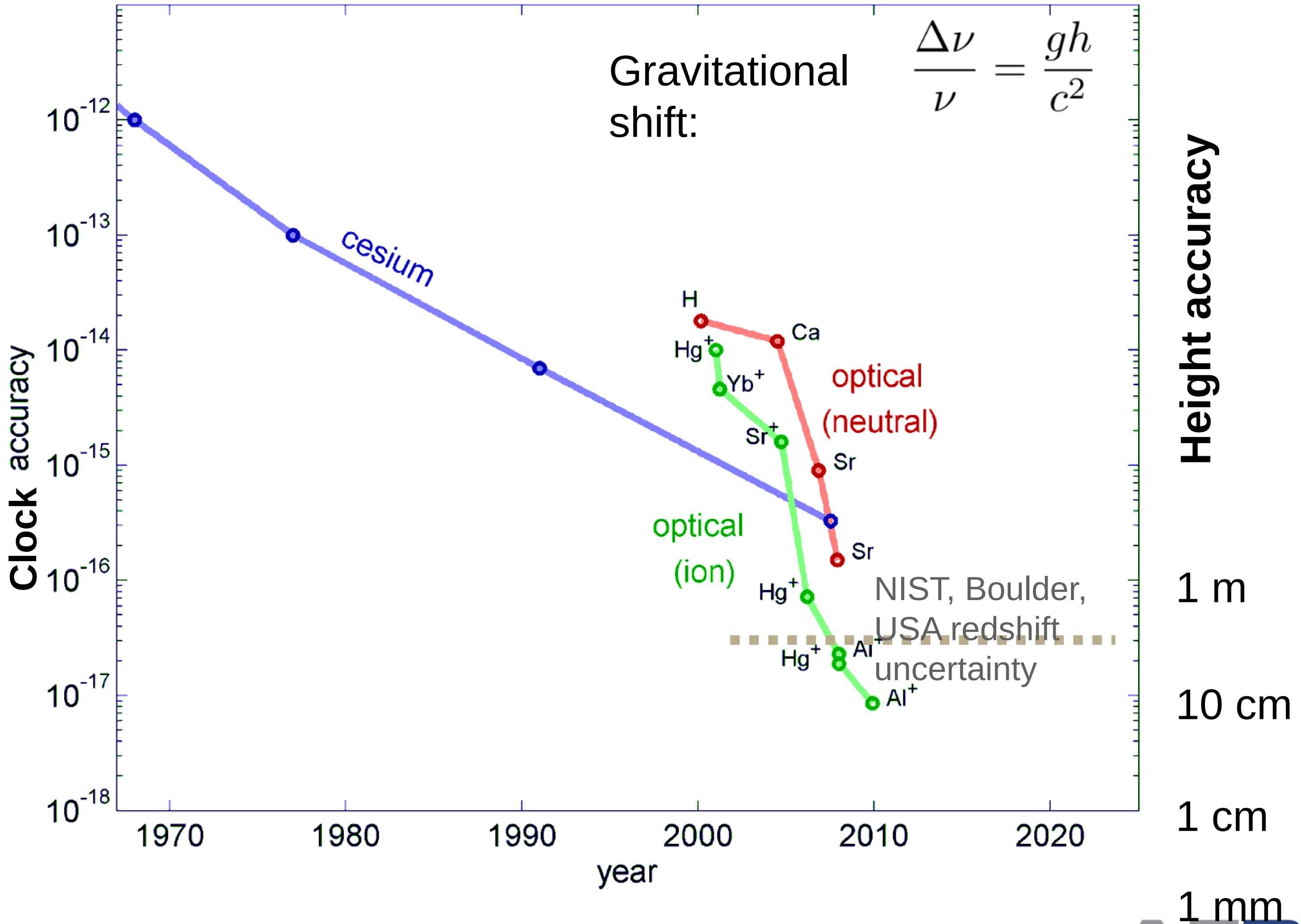
$T/T_F = 0.25$

manuscript in preparation

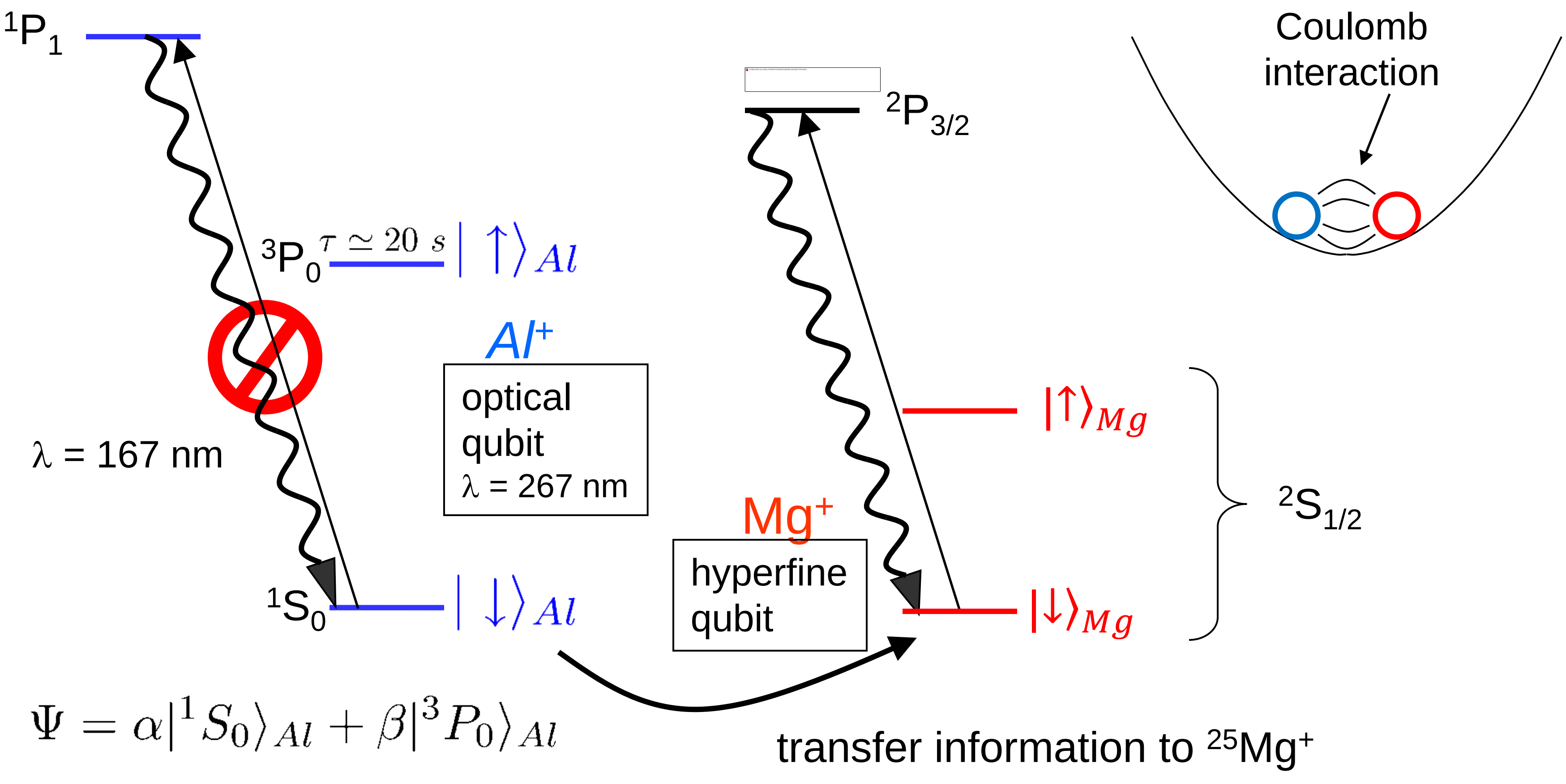
Outline

- Quantum Simulation, Strongly-Interacting Quantum Gases
  - Bosons: Markus Greiner, Harvard (MURI)
    - Algorithmic Cooling in Quantum Gases
      Waseem Bakr, *et al, Nature* **480**, 500 (2011)
    - Quantum Magnetism
      Jonathan Simon, *et al, Nature* **472**, 307 (2011)
  - Fermions: Martin Zwierlein, MIT (PECASE, MURI)
    - Evolution of Fermi Pairing from 3D to 2D
      Ariel T. Sommer, *et al, Phys. Rev. Lett*. **108**, 045302 (2012)
    - Spin Transport in a Strongly-Interacting Fermi Gas
      Ariel Sommer, *et al, Nature* **472**, 201 (2011)
    - Thermodynamics of a Unitary Fermi Gas: Superfluid Lambda Transition
      Mark J.H. Ku, *et al, Science* (in print); K. Van Houcke, *et al* (submitted to *Nature Physics)*
- Dipolar Matter: Benjamin Lev, UIUC/Stanford (YIP)
  - Dy BEC, and First Dipolar Degenerate Fermi Gas
    Mingwu Lu, *et al, Phys. Rev. Lett.* **107**, 190401 (2011)
- **Quantum Metrology: Till Rosenband, NIST**
  - **Coherent Drive Spectroscopy**
    D.B. Hume, *et al, Phys. Rev. Lett.* **107**, 243902 (2011)

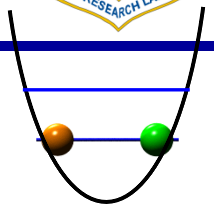
Motivation: Al^+ clock accuracy



Quantum Logic Spectroscopy

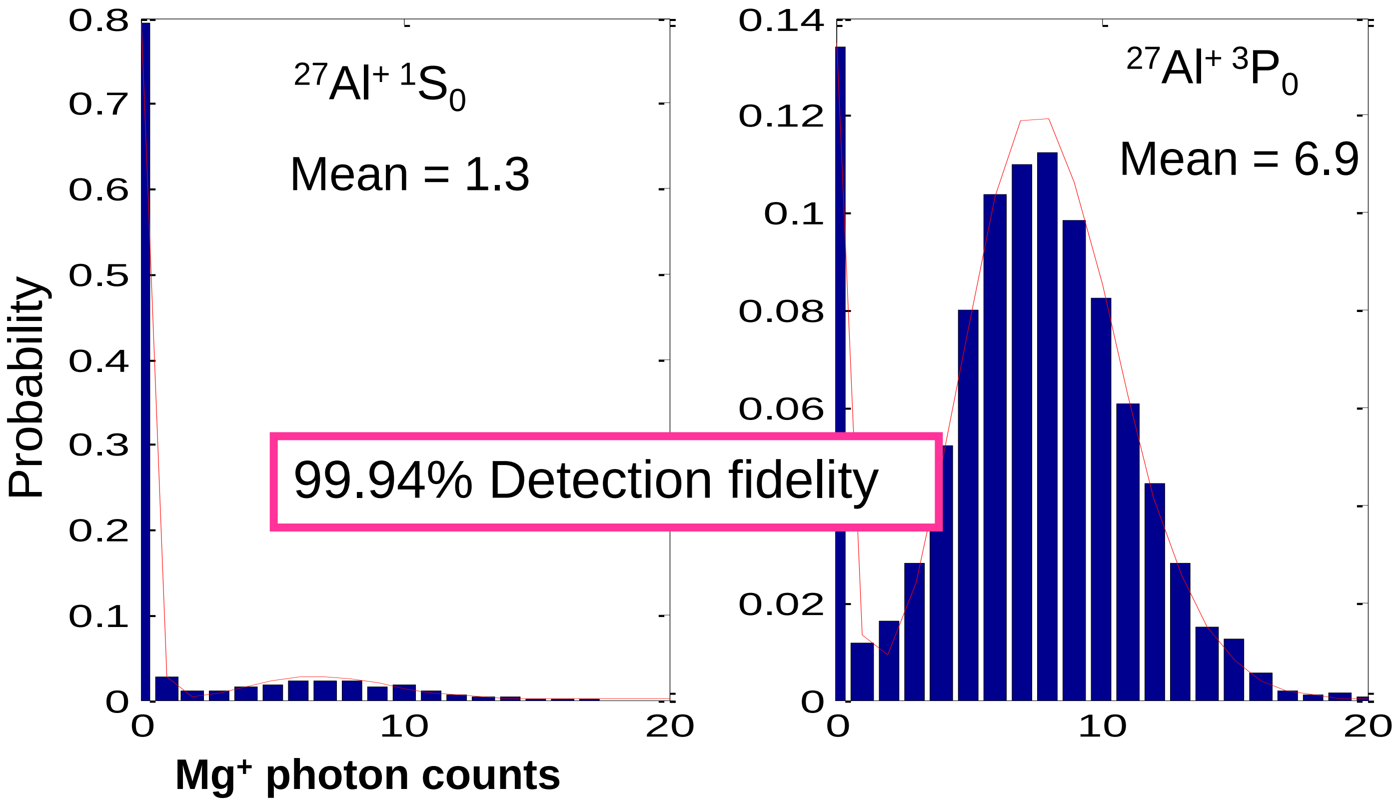


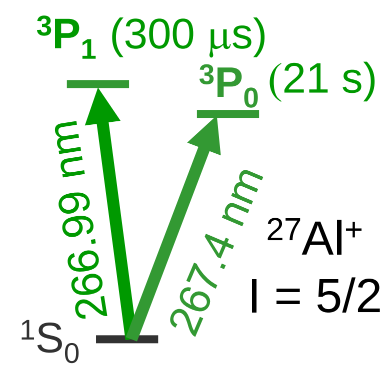
Al^{+} quantum-logic spectroscopy



QND

1. Cool to motional ground-state with Mg^{+} (Raman cooling)
2. Depending on Al^{+} clock state, add one vibrational quantum via $^1S_0$-$^3P_1$
3. Detect vibrational quantum with Mg^{+}





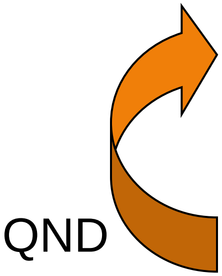
P.O. Schmidt, *et al.* *Science* **309**, 749 (2005)

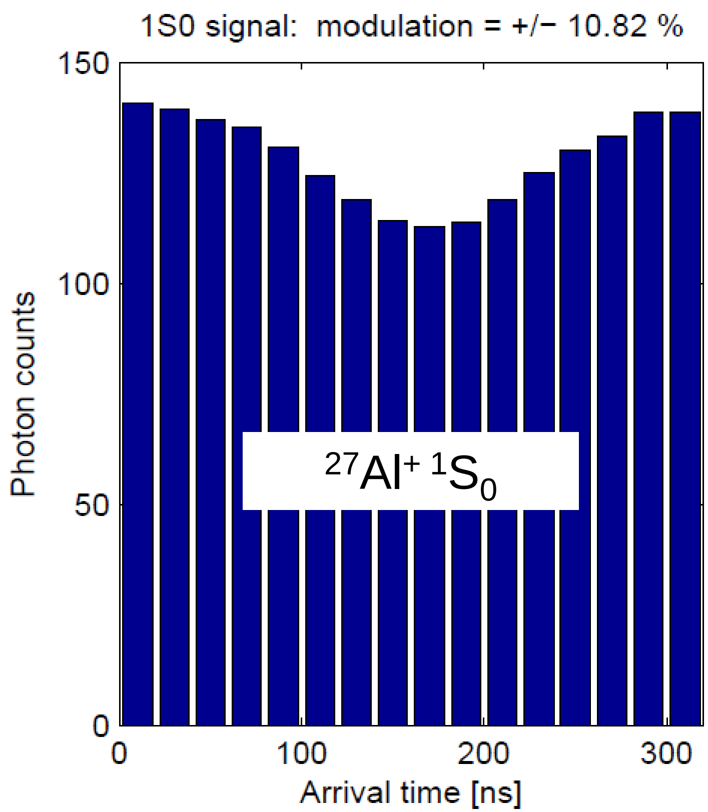
D. B. Hume, *et al.* PRL **99**, 120502 (2007)

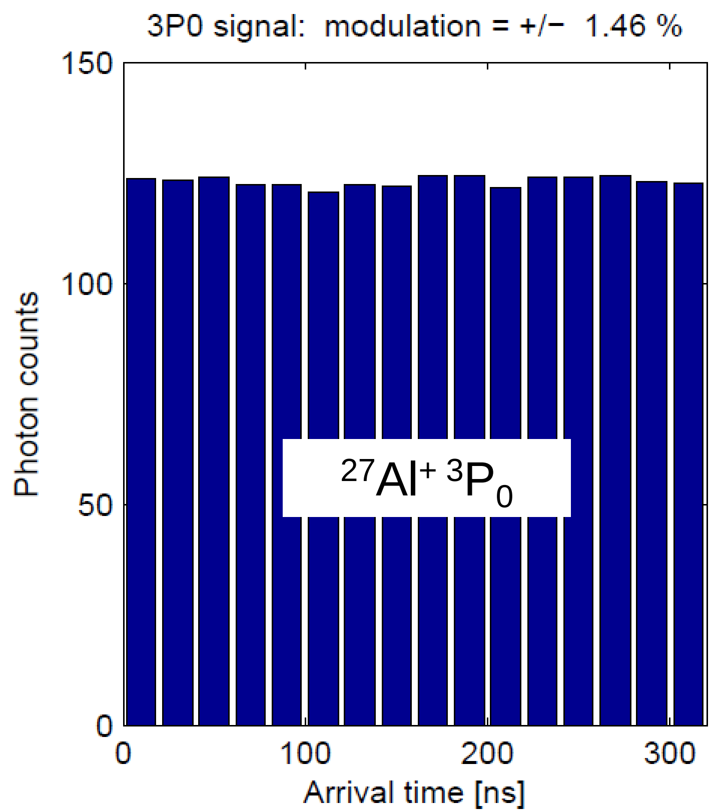
Al^+ ~~quantum-logic~~ coherent-drive spectroscopy

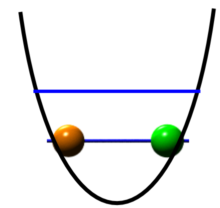
Mg⁺ Doppler

1. ~~Cool to motional ground state with Mg⁺ (Raman~~ cooling)
2. Depending on Al⁺ clock state, ~~add one vibrational quantum~~ drive coherent motion via $^1S_0$-$^3P_1$
3. Detect ~~vibrational quantum~~ coherent motion with Mg⁺

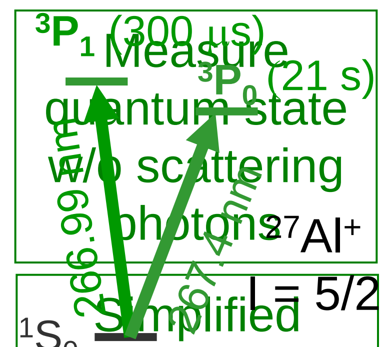








D. B. Hume, *et al.*
PRL 107, 243902 (2011)



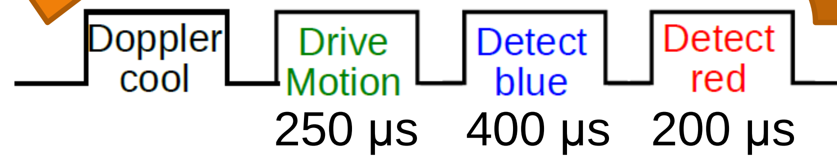
Measure quantum state w/o scattering photons

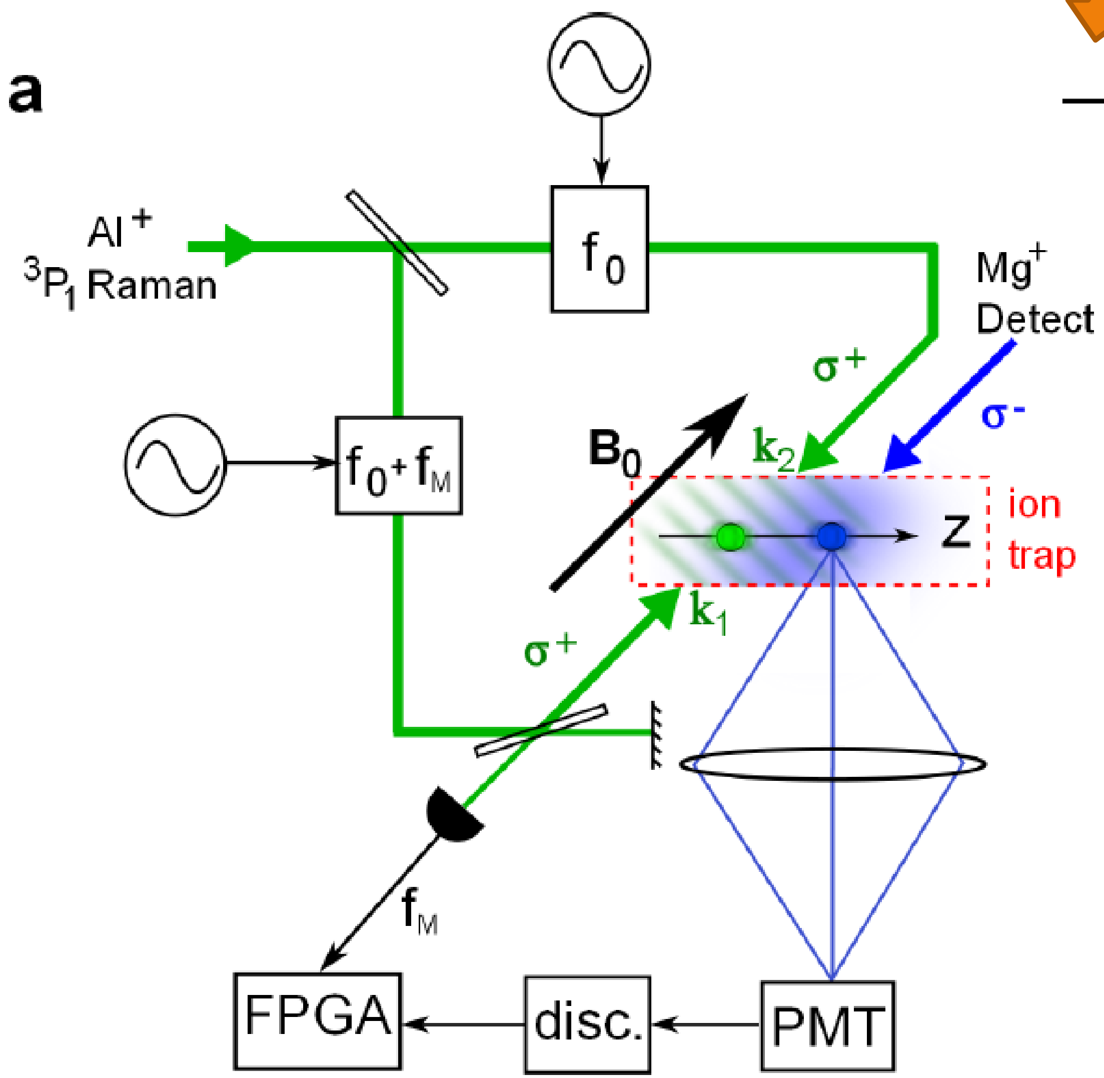
Simplified lasers (no ground-state cooling)

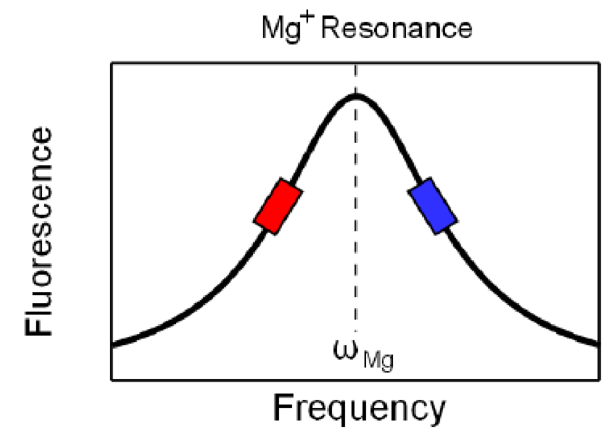
Slower

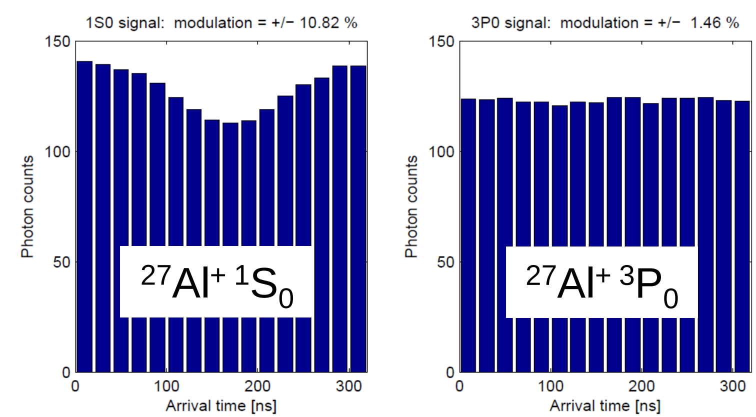
Al^+ coherent-drive spectroscopy

D. B. Hume, et al., PRL107, 243902 (2011)



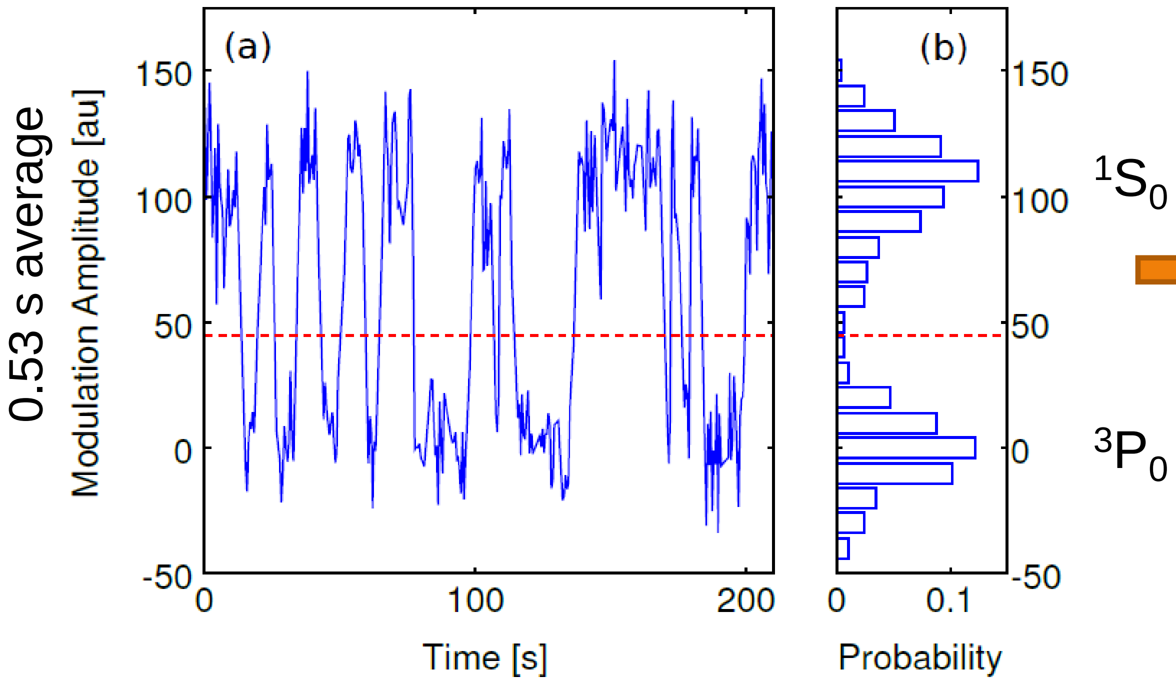






Quantum Jumps

Quantum jumps between clock states ($^1S_0$ and $^3P_0$)



93% state-detection fidelity within 80 ms

with quantum logic: 99% within 10 ms

- Coherent drive detection rate could be improved by higher modulation amplitude or photon collection efficiency
- Can be generalized for more than one Al^+ ion

Interactions with Other Agencies

Agency/Group	POC	Scientific Area
ARO	Peter Reynolds Paul Baker	Cold Quantum Gases (CQG)
	TR Govindan	Quantum Information Science (QIS)
	Rich Hammond	Ultrafast/Ultraintense Phenomena (UUP)
ONR	Charles Clark	CQG, QIS
	Ralph Wachter	QIS
DARPA	Jamil Abo-Shaeer	CQG, QIS
	Jag Shah	QIS
	Matt Goodman	QIS
NSF	Wendell Hill	CQG, QIS, UUP
DoE	Jeff Krause	CQG, UUP
IARPA	Michael Mandelberg	QIS
QISCOG	>20 program managers from ~10 agencies/institutions	QIS

Thank you